7-7-2016

Development of a Decentralized and Off-grid Anaerobic Membrane Bioreactor (AnMBR) for Urban Sanitation in Developing Countries

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Development of a Decentralized and Off-grid Anaerobic Membrane Bioreactor (AnMBR) for Urban Sanitation in Developing Countries

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Environmental Engineering
Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

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Date of Approval:
June 14, 2016

Keywords: wastewater, water recycling, nutrient, energy, India

Acknowledgments

I want to thank all of the agencies whose financial support made this research possible. Specifically, The National Science Foundation's Students, Teachers, and Resources in the Sciences fellowship; The Bill and Melinda Gates Foundation for their Grand Challenges Exploration Grant; The National Science Foundation for funding under Grant No. 1243510; India's Biotechnology Industry Research Assistance Council for their Reinvent the Toilet Challenge – India Grant; and The Cade Museum for their 2014 Cade Museum Prize. I also want to thank the Department of Education's Graduate Assistance in Areas of National Need Grant (GAANN) for financial support.

I would also like to thank my committee members, Dr. Y. Goswami, Prof. P. Lens, Dr. J. Cunningham, and Dr. R. Zarger for their expertise and guidance in this process. I want to express my gratitude to Midhu S. V., Dijin, and all the staff at Eram Scientific Solutions for their assistance in India. I also want to thank Pentair X-Flow for their technical guidance. The TRL7 system benefited from sponsorship by Pentair, Charleston Marine Containers, Inc., Trojan Battery Company and WaterStep. I want to thank the staff at Learning Gate Community School for allowing a pilot on their campus. I am greatly indebted to Dr. A. L. Prieto, who taught me the ways of the membrane master; as well as Dr. A. Do; and Dr. R. Ferlita, Dr. A. Buttice, and Dr. S. DuPont. I would like to thank the efficient Dr. I. Drexler; the deep-minded, O. Ozcan; the meticulous, Dr. C. Joustra; the ambitious, Dr. J. Ariunbaatar; the nutrient master, J. Calabria; and the driven, Dr. P. Dolejs.

I also want to thank all of those I have had the pleasure to share the lab. Specifically, G. Dick, P. Zydek, N. de Hart, A. Filippi, H. Jean, M. Woodham, W. Sutton, J. Duran, and C. Agbim. Outside of the lab, I am greatly indebted to my friends and family, especially Adventure Points, members of the Lake House, and my loving parents. Above all, I want to thank my adviser, Dr. Daniel Yeh for his leadership, encouragement, advice, and persistence in this whole ordeal. Without his support there is little chance that I would have embarked on or completed this journey.

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Abstract

Urbanization has led to rapid and uncontrolled growth of informal housing settlements in many developing countries. As most slum growth is unplanned, these areas tend to lack basic infrastructure including sanitation. The high user rates, lack of water and electricity infrastructure, space limitations, and scant financial resources make sanitation provision a major challenge in slums. As most decentralized sanitation technologies fail when applied in these environments, better technologies need to be developed that cater to the specific needs of slum dwellers. One promising technology, the membrane bioreactor (MBR) is routinely used in developed countries when a compact and resilient treatment system is required. However, the energy requirement of existing MBRs is high, as most are aerobic systems which require aeration. Anaerobic MBRs (AnMBR), which do not require aeration, have led to an improvement of the energy profile of MBRs. As research into the technology is still in its infancy, little is known regarding its applicability in high-density urban environments. This body of research is aimed at understanding the AnMBR's treatment performance and overall reliability in challenging circumstances similar to those encountered in slums.

The appropriateness of an AnMBR was investigated with pilot and full-scale systems treating real wastewater in field conditions. The first investigation, discussed in Chapter 3, was used to determine the resilience of AnMBR treatment when subjected to periods of disuse and high fluctuations in incoming feed strengths. Decentralized systems often see much higher variations in feed composition than centralized systems as they lack large collection systems which homogenize the influent wastewater. Depending on the application, periods of low and no flow are also possible. During this long-term study it was observed that the membrane served an important role in controlling the effluent quality, especially when environmental conditions and feed characteristics varied so significantly as to upset biological stability. The system achieved an average COD removal efficiency of 88.2% throughout the study. It was

also observed during this study that the system had higher removal efficiencies when treating higher COD concentrations. Higher strength wastewaters can routinely be found in decentralized applications where dilution water is minimal. These locations include water-efficient buildings, direct coupling to public toilets, and fecal sludge treatment plants. It was also found that the AnMBR was capable of rapidly recovering from extended periods of disuse. This ensures that the AnMBR can be applied to areas, such as schools and hotels that experience large seasonal variations and periods of disuse.

The second investigation, described in Chapter 4, examined how fluctuations in ambient temperatures affect fouling resistance. In small decentralized applications, operating the reactor at ambient temperatures is the most likely scenario, as controlling the reactor temperature would incur a high energy demand. Operating at ambient temperatures means that variations can be high, and that temperatures can drop below ideal ranges. Temperature is known to affect biological treatment and to a lesser extent membrane filtration, but the interactions between the two are not fully understood. To determine the effect of temperature on operation, a pilot scale AnMBR was used to treat wastewater with fluctuating ambient temperatures. Three trials were conducted during summer and winter conditions, as well an artificially heated period. It was found that membrane permeability can be greatly affected by operating temperature but its effect varied depending on the fouling state of the membrane. Virgin, or recently cleaned membranes were not affected by low temperatures, while the permeability of slightly fouled membranes was negatively correlated to changes in temperature. When slightly fouled, a membrane TMP could increase by 2.4 times with a 10^{o}C drop in temperature. The magnitude of the TMP increase could not be explained by changes in water viscosity alone. The effect of temperature on TMP decreased when fouling became severe and normal operating pressures were high. These results suggest that seasonal adjustments to AnMBR operation would be necessary to prevent sharp and excessive increases in operational TMP during cold spells.

Chapter 5 investigated the feasibility of recovering water, nutrients, and energy in an off-grid and decentralized AnMBR. This investigation performed an energy, nutrient, and mass balance for a theoretical AnMBR treating water from a public toilet in a high density setting. What was concluded from this study is that complete water recycling can be accomplished in such an environment. Onsite water recycling would allow the system to be applied in arid urban areas as well as places lacking regular water provision. The study also concluded that the energy content of wastewater in a high density area would be sufficient to power an AnMBR and electronic toilet. For areas where low wastewater strengths would be expected, food waste addition to the wastewater would improve the energy profile of the system. As many urban areas of developing countries struggle with solid waste management, there is the opportunity to link food waste management with wastewater treatment. This study also highlighted the potential problems that ammonia and salinity buildup could have on a system that achieves complete water recycling.

Once the system specifically designed for urban areas was deemed theoretically feasible, a full-scale, solar-powered, prototypical system was constructed in Florida and tested in India (Chapter 6). This system, which was applied in Kerala, India, was investigated for its treatment and membrane performance as well as energy consumption. During the first four months of operation, the system was able to produce high quality product water that could be used for toilet flushing. This was achieved despite the low strength of the incoming feed water and higher than anticipated wastewater production rates. The wastewater strength was low due to the system's application in a school setting and high levels of dilution water. The reliance on multiple anti-fouling mechanisms allowed the system to operate for 4 months without a significant change in TMP. The average energy consumption per unit of produced water depended on the amount of water treated per day. On average the energy consumption was 1.52 kWh/m^3, but that value dropped to 0.83 kWh/m^3 when volumes greater than 200 liters were treated per day. The lowest value measured during this trial was 0.16 kWh/m^3 when 1,394 liters were produced. All of the energy used by the system was produced by onsite photovoltaics, with minimal carbon footprint. While the system was capable of meeting the water demand of the toilet system, further improvements in the energy demand of the system will be necessary to make the system more cost-effective, robust and reliable.

These results suggest that AnMBRs can be applied in high density urban areas for the dual objectives of wastewater treatment and resource recovery. Their reliable treatment in the face of large fluctuations in feed concentration, volume, and temperature suggests they are appropriate for decentralized applications. Membrane filtration allows water to be reliably recycled onsite with minimal operator oversight. The low energy requirements of the system allow for onsite renewable energy sourced, such as photovoltaics to be used to power the system. AnMBRs are able to address many of the challenges that traditional sanitation technologies cannot, which makes them a promising technology to address the problems encountered in slum sanitation.

Chapter 1: Introduction

This body of research stems from the need that exists for more appropriate sanitation technologies and an understanding of the short-comings of those currently used by the world's urban poor. This research contributes towards the development of a decentralized wastewater treatment technology that meets the unique challenges encountered in urban sanitation in developing countries. The aim is to develop a technology that is capable of providing effective treatment of human waste while recovering water, nutrients, and energy.

1.1 The Global Sanitation Challenge

The global task of providing adequate sanitation has proven to be a daunting challenge. Despite numerous interventions by nongovernmental organizations (NGOs), governments, community based organizations (CBOs), approximately 2.4 billion people still lack access to adequate sanitation (United Nations, 2015). Within this category, an estimated 1 billion still resort to the practice of open defecation, resulting in rapid environmental degradation and a heavy disease burden for local populations (United Nations, 2015). When lack of sanitation coincides with insufficient hygiene and drinking water treatment, community health is adversely affected. The World Health Organization (WHO) estimates that 9.1% of the global disease burden and 6.3% of all global deaths can be attributed to problems in water, sanitation and hygiene provision (Prüss-Üstün et al., 2008). Chronic diarrhea, which has its roots in sanitation, accounts for approximately 801,000 child deaths every year (Liu et al., 2012). The importance of addressing the sanitation problem is clear, however a universal solution to sanitation does not exist. Diverse cultural, environmental, political, and economic situations require unique solutions for appropriate implementation (Holden, 2008).

Those affected by a lack of sanitation are primarily the world's poor living in developing countries. The vast majority of those still practicing open defecation are located in Asia and Sub-Saharan

Africa (United Nations, 2015). The sanitation problem is compounded by additional pressures affecting those same areas including: global climate change, population growth, and urbanization. Some of the effects of climate change, including increased droughts, or increased rainfall events can affect sanitation in negative ways. In areas where increased drought is expected, sewerage and its associated water use will place an additional burden on water resources and infrastructure (World Health Organization, 2009; Howard et al., 2010). In areas where flooding events are expected to increase, many traditional sanitation technologies will be overwhelmed and result in pathogen transmission (World Health Organization, 2009; Howard et al., 2010). As global communities continue to grow, population growth will exert pressure on the existing sanitation infrastructure. In many of the countries already experiencing sanitation problems, their population growth rates are higher than the global average (World Health Organization, 2009). These governments are already unable to provide sufficient infrastructure; the possibility of meeting future demand with even larger populations is bleak. An additional strain on infrastructure comes from urbanization, as more rural people crowd into the congested cities of developing countries seeking employment. Urbanization is expected to continue bringing rural citizens into cities at an average growth rate of 1.5%, which will result in an additional 2 billion people in cities by 2040 (UN-Habitat, 2003). Although the vast majority of people lacking sanitation in today's world are located in rural areas, trends like urbanization and the unique engineering challenges presented by high-density urban areas, make urban sanitation an important area of research.

1.2 Urban Sanitation: Challenges and Criteria

Slum dwellers are some of the most vulnerable and impoverished citizens of urban centers (Holden, 2008). For a technology to be widely and sustainability used in a city, it must meet the specific needs of this segment of society. The Millennium Development Goal of achieving "significant improvement in the lives of at least 100 million slum dwellers," has been met and exceeded (United Nations, 2015). While the significance of this achievement should not be disregarded, it is overshadowed by an overall growth in slum dwellers from 760 million in 2000, to 863 million in 2012 (United Nations, 2013). Greater job prospects and the amenities of cities lure rural residents into urban areas. However, as is the case with most rural migrants, they find themselves entering the squalid conditions of slums. In countries like Rwanda, Nigeria, Uganda, and Bangladesh more than 50% of the urban population lives in slums (United Nations, 2013). Some mega-cities like Mumbai, India, have over 12 million people living in its slums (Nijman, 2008).

Slums or informal housing sectors are characterized by their lack of official land tenure (UN-Habitat, 2003). Slum dwellers build makeshift shelters on government, private or undesirable lands located within or near cities (Holden, 2008). Local governments are often unwilling to provide basic utilities to these areas due to their illegal nature (Schouten and Mathenge, 2010). Most slum dwellers are also unwilling to make large capital investments in their shelters because of their precarious legal status and lack of financial resources. This leaves slums without substantial infrastructure development. Electricity, if available, is often unreliable as a result of numerous blackouts and brownouts. Most of water sources are heavily contaminated due to local industries, solid waste mismanagement and a lack of sanitation. It is also common for slum dwellers to pay premium prices for drinking water caused by the lack of centralized water infrastructure (UN-Habitat, 2003; Katukiza et al., 2012). Sanitation technologies that rely on grid connected sewerage, reliable electricity, or even water connections are not appropriate for slums (Schouten and Mathenge, 2010; Katukiza et al., 2012). Additionally, centralized sewerage can prove to be impractical, if not impossible for these precarious illegal settlements (Paterson et al., 2007; Katukiza et al., 2010).

Slums are also characterized by high population densities. Kibera, one of the largest slums in Africa, is reported to have over 2000 people per hectare (Schouten and Mathenge, 2010). These cramped conditions can make land within slums a scarce commodity. Those who claim land in a slum prefer to create rentable living space or businesses as opposed to building toilets on their land. This leads to very few sanitation options being shared amongst many people. Shared, communal and public toilets as opposed to private toilets are common options for slum dwellers and have been considered the only viable option for slum dwellers by some authors due to these space constraints (Paterson et al., 2007; Schouten and Mathenge, 2010). In Kibera, it was reported that up to 150 people per day shared a single pit latrine

(Schouten and Mathenge, 2010). Higher rates of up to 650 people were observed using a single toilet block (8-9 toilets in the communal toilet block) in Kampala, Uganda (Katukiza et al., 2010). High rates of toilet usage can easily overwhelm traditional low-cost treatment systems and lead to dangerous sanitary conditions such as overflows and backups. High user rates tend to decrease aesthetic performance due to dirty condition and foul smells. The high density also leads to poor accessibility within slums. Transportation of materials to a construction site and the removal of waste products are exceedingly difficult due the narrow and uneven passageways found in most slums (Paterson et al., 2007; Katukiza et al., 2012). Technologies developed for urban sanitation need to take into consideration the unique challenges encountered in slums if they are to be widely applied and to be relevant to the poorest of urban dwellers (Katukiza et al., 2012). The lack of legal land ownership, low water provisions, unreliable electrical provisions, high-user rates, low space availability, low accessibility, and scant financial resources of slum dwellers combine to make urban sanitation a very unique engineering challenge that demands urgent attention.

1.3 Current Sanitation Technologies in Marginalized Urban Areas

A variety of sanitation technologies are currently in use by slum dwellers to help address their sanitation needs. What follows is a list with brief descriptions and related shortcomings of the technologies already in use. The list is ordered to reflect the sanitation ladder where the simplest/least hygienic methods of waste disposal are presented first. As one goes up the sanitation ladder, the cost of the technology increases as well all as the overall societal/user benefit provided by the technology.

1.3.1 Open Defecation

Open defecation results when no technological intervention is available to prevent the release of human excreta into the environment. Open defecation is at the base of the sanitation ladder, as it provides no tangible societal or user benefit. With open defecation, pathogens and organics deposited throughout the environment by humans are then dispersed by rainfall, traffic, animals and insects. In congested urban areas, those that resort to open defecation do so in public spaces including railways, roads, beaches, river banks, and parks which then makes these locations reservoirs of disease (Udas, 2012). The negative health and environmental consequences of open defecation are only paralleled by its impact on society. Women and girls are particularly vulnerable to sexual abuse when defecating in the early mornings or after dark (Lennon, 2011). A lack of privacy drives many women and girls to openly defecate in these twilight hours to avoid embarrassment (Lennon, 2011). Open defecation is a blight on society and needs to be replaced with more hygienic and dignified forms of sanitation.

1.3.2 Flying Toilets

A flying toilet is the practice of urinating and defecating in a plastic bag, bottle or container and disposing of it within the local area. Flying toilets are common in slums due to their convenience and low cost. However, disposal typically means discarding containers in the immediate area, on roadsides or along with solid waste (Gulis et al., 2004). These containers can rupture, leading to the dispersal of the contents, rendering them little better than open defecation. Flying toilets also jeopardized the health of trash scavengers who sort through solid waste looking for recyclable materials.

There are organizations that work at improving the use of flying toilets. One organization, Peepoople® has created the Peepoo bag which is an inexpensive biodegradable bag that contains urea for disinfection (Katukiza et al., 2012). These bags allow for nutrient recovery when they are disposed of in gardens. This technology was found to be an adequate solution to the crisis that resulted in Haiti after the 2010 earthquake (Coloni et al., 2012). While this contribution is valuable for short term sanitation provision, or in the case of emergencies, it is not considered a long-term viable option for slums as many people find the practice degrading (Schouten and Mathenge, 2010).

1.3.3 Pit Latrines

Unimproved pit latrines include unlined holes in the ground which have some form of platform for the user to squat on. Human waste, cleansing materials and some solid waste end up collecting within the pits. A limited amount of biological activity and dewatering of the fecal material occurs while in the pit (Paterson et al., 2007). Dewatering depends greatly on the soil characteristics and on the water level, with high water tables contributing towards waterlogging of pit (Koné and Strauss, 2004). Pit latrines are relatively inexpensive and require little maintenance, which makes them one of the most common sanitation technologies in use today (Thye et al., 2011). However, they are often smelly, lack privacy and can be unhygienic when using a soil or wood platform (Grimason et al., 2000). Helminths, or eukaryotic parasites, are known to be transmitted through user's feet when a soil or wooden platform is used (Wagner and Lanoix, 1958). A simple modification that improves the sanitation value of a pit latrine is the addition of a cement platform. Further improvements, including the design of a Ventilated Improved Pit (VIP) latrine can also result in enhanced sanitation. VIP latrines are built to improve ventilation in the superstructure, and are better suited to control odors and flies (Wagner and Lanoix, 1958; Katukiza et al., 2010).

Pit latrines can serve a valuable role in rural areas, where population density does not interfere with the functioning of the latrine (Satterthwaite, 2016). In urban areas, pit latrines fill rapidly, in a matter of weeks or days as was witnessed by Schouten & Mathenge (2010). When these pits fill, they are usually emptied or in the worst case scenarios, are abandoned. When emptied, the contents are handled by locals who primarily discard the material in open water bodies, ditches or other convenient locations rather than official fecal sludge management facilities (Koné and Strauss, 2004; Holden, 2008). Since minimal inactivation of pathogens occurs within the pit, the pit cleaners are re-exposed to the pathogens and the inadequate disposal of pit contents can make pit latrines little better than open defecation.

Pit latrines can also contaminate ground and surface water when the water table is high. Many slums are located in low-lying flood prone areas, which increases the probability that the pits can become flooded (Katukiza et al., 2010). The likelihood of flooding is increased in coastal areas suffering from the effects of climate change. Flooding of a pit latrine negates the sanitation benefits from having this technology, as fecal material is then carried with the water into the surrounding houses, wells and environment. Pit latrines, although commonly used, have many technological limitations regarding their implementation in high-density settings where high user input is expected.

1.3.4 Ecological Sanitation

Ecological sanitation, or EcoSan, encompasses a few broad types of sanitation technologies that allow for the sustainable recovery and reuse of the nutrients and carbon in human waste. This section will focus on urine-diverting dry toilets (UDDT) and composting latrines. UDDTs aim to immediately separate urine and feces at the source of production. The rationale behind this is that urine contains the majority of the nitrogen and phosphorus excreted by the body while containing few pathogens. The urine can then be stored for a few months and directly applied as a fertilizer to plants (Mihelcic, 2009). The feces enter a separate vault where they are allowed to dry, which inactivates pathogens contained in the waste. Composting latrines separate the urine, but they use aerobic decomposition and heat to help inactivate pathogens and to prepare the feces to be used as a fertilizer and soil conditioner. Composting toilets have been used successfully in Port-au-Prince, Haiti by an NGO called Sustainable Organic Integrated Livelihoods (SOIL) where compost from over 20,000 city dwellers is used to raise food in the local city (Berendes et al., 2013)

EcoSan technologies are beneficial in that they allow for the sustainable reuse of the nutrients and carbon found in human waste. They also require little to no water for their functioning. However, in the case of composting toilets they do require an additional carbon source to provide the adequate C:N ratio required to compost (Mihelcic, 2009). This is usually accomplished through the addition of sawdust, ash or in the case of SOIL, sugarcane husks. EcoSan toilets in field conditions have been found to have unreliable pathogen inactivation due to insufficient heat and or high enough pH values (Anand and Apul, 2013). There are also cultural barriers to Ecosan toilets which include a negative image of the technology, an unwillingness to perform sufficient maintenance, and lack of access to bulking materials (Fenner et al., 2007; Anand and Apul, 2013). Careful monitoring, proper upkeep, and social considerations are required to provide a sufficient level of treatment when using Ecosan methods.

1.3.5 Biogas Toilets

Biogas toilets are toilets that use anaerobic microbes to break down human waste and convert the organic material into biogas and liquid and solid fertilizers. Biogas toilets are typically used in conjunction with agriculture where large volumes of organic waste can supplement the small quantity of human waste that is generated by a household. India and China have over 27 million domestic digesters used primarily for agricultural waste processing (Bond and Templeton, 2011). To a lesser degree, biogas toilets have been used for the sole purpose of human waste processing usually in combination with communal toilet blocks. Biogas toilets provide for some pathogen removal while recovering embodied energy from wastewater in the form of biogas. Biogas, which is primarily a mixture of methane and carbon dioxide, can be combusted on-site to help offset energy demand for cooking, heating and electrical generation. Biogas toilets have the added benefit of reducing the solids content of the waste through microbial degradation. This allows for minimal removal of solids from the site of generation. However, in practice biogas toilets have some limitations, including cost, odor issues and complexity due to the nature of the biological system. Due to their size requirements and daily maintenance schedules, these systems are almost exclusively found in rural locations. Biogas toilets can also be more expensive; in Kibera they were 3 to 4 times more expensive than improved pit latrines (Schouten and Mathenge, 2010). The cost is often a prohibitive barrier to implementation. Schouten and Mathenge (2010) reported that slum dwellers found biogas toilets to be smelly and provided an inferior user experience [1]when compared to other sanitation technologies. Lastly, this technology relies on a complex microbial consortia to function properly. Improper maintenance, large organic loadings, pH changes and temperature fluctuations can cause failure or reduced performance. Failures in the biological system can cause owners to lose faith in the technology resulting in abandonment or lack of adequate maintenance.

1.3.6 Pour Flush Toilets

Pour flush toilets represent a significant improvement over simple pit latrines in terms of hygiene and user experience. Pour flush toilets use water as a medium to carry human waste away from the toilet and into a treatment system or holding tank. A water seal in the toilet pan prevents insects and odors from coming back into the toilet area. A water seal allows these toilets to be located inside of a home instead of being located outside. Some toilets are followed by a septic tank or leach pit. Septic tanks and leach pits

[1] Schouten & Mathenge (2010), also linked the poor user experience to the inadequate design of the biogas facility. Human feces remained exposed under the toilet for prolonged periods of time before they were placed into the anaerobic reactor. Better design of these facilities can lead to improved user acceptance.

must be periodically emptied every, 3-4 years depending on use (Wagner and Lanoix, 1958). The practice of emptying septic tanks and leach pits have similar consequences to those of emptying pit latrines, which include illegal dumping of collected sludge and pathogen transmission to sanitation workers (Koné and Strauss, 2004). While these solutions provide the best user experience, they can be quite expensive to construct and operate. They require a continuous source of water for flushing purposes which makes them less relevant to water stressed areas. When combined with a septic tank and leach field, the space requirements can be quite high. Septic tanks rely on soil infiltration for final disposal of the treated wastewater, which makes the technology vulnerable to high water tables and floods. Pour flush toilets, when connected to a leach pit or septic tank, present a challenge in slums due to their footprint, initial capital cost, emptying requirements and their requirement for a water connection. They also do not allow for localized reuse of nutrients, energy or treated water, which makes them a less sustainable option for sanitation.

1.3.7 Simplified Sewerage

Simplified sewerage was developed in Brazil in the 1980s and is a method of using smaller pipe diameters and above ground piping to transport human waste away from the point of generation and to the official city sewers or another point of treatment (Paterson et al., 2007). The smaller pipe diameters allow smaller volumes of water to be conveyed while creating a higher velocity flow in the pipe network. By placing the pipes above ground, the network can be installed within unplanned and cramped informal housing developments. Simplified sewerage is currently in use in slums throughout Asia, Latin America and Africa. Simplified sewerage can be considered an appropriate technology in areas where water connection is available for pour-flush toilets. In areas where ample water is not available, simplified sewerage is not appropriate. Simplified sewerage also relies on off-site treatment of the wastewater that is produced, which means that localized reuse of the water and nutrients are not possible.

1.4 Current Technology Lessons and Summary

Despite their shortcomings and limitations, all of the previously described technologies are used in slums. Innovations are required to produce novel, reliable and sustainable technologies that can address the unique challenges found in slums. These technologies should recover energy, water and nutrients from wastewater and make them available to the local community in culturally acceptable ways (Paterson et al., 2007; Murphy et al., 2009). They should also be able to deal with the lack of water and energy infrastructure which is so common to many informal housing areas. Lower production of sludge waste will help decrease the cost and health risk associated with waste removal. Complete pathogen destruction at decentralized facilities can also ensure the safety of sanitation workers. What is desired is a disruptive, pro-poor sanitation technology that is technologically and environmentally sound and that is desirable to its users. A desire for technologies that fit these criteria coincides with a recent paradigm shift in many developing countries favoring the adoption of better performing, high-end technologies (Ujang and Henze, 2006). If a technology is found that can meet the expectations of slum conditions, then it can be easily adopted to solve many of the problems of urban sanitation in developing countries.

1.5 The Promise of Membrane Technology

One of the most promising technologies for decentralized wastewater treatment is the membrane bioreactor (MBR) (DiGiano et al., 2004). A simplified definition of a MBR is a combination of a biological process and membrane separation (Drews and Kraume, 2005). Membranes, which are made of semi-permeable materials, fall into four categories depending on their pore size and filtration mechanism, these include reverse osmosis, nanofiltration, ultrafiltration and microfiltration membranes. Ultrafiltration (0.01-0.05 µm pore size) and microfiltration membranes (0.2- 10 µm pore size) are the most commonly used membranes in wastewater treatment systems (Allgeier et al., 2005; Crittenden et al., 2012). Within the wastewater treatment sector, MBRs have a number of advantages over conventional activated sludge (CAS) processes. MBRs are able to increase the cell concentrations within bioreactors which results in increased in microbial activity (Drews and Kraume, 2005). By increasing microbial activity, the reactor size can be minimized while still achieving a high treatment efficiency. This means that MBRs are suitable for areas where a small footprint is required. Complete retention of biomass within the reactor also means that MBRs are not constrained by poorly settling biomass, which would normally bypass gravity based settling tanks. MBRs are also used in areas where water reuse is of great importance as they can reliably deliver higher quality water than what is required by most reuse standards (Pellegrin et al., 2013). MBR operation can also be automated to a greater extent than conventional treatment systems allowing for more decentralized treatment (DiGiano et al., 2004; Kraemer et al., 2012). MBRs for wastewater treatment have been around since the 1970s, however large-scale implementation didn't start blooming until the 1990s (Yang et al., 2006; Kraemer et al., 2012). A significant amount of research has gone into making MBRs more robust and energy efficient leading to a general consensus amongst practitioners that MBRs are approaching the status of a mature technology for municipal wastewater treatment (DiGiano et al., 2004; Kraemer et al., 2012).

The Bellagio framework, developed in 2004 by a team of water and sustainability experts from around the world, declared that MBRs will be essential in advancing sustainability, water reuse and decentralization in developed and developing countries (DiGiano et al., 2004). Industry leaders have promoted similar views, declaring that developing countries stand to gain the most from MBR implementation (Daigger et al., 2005).The Bellagio framework identified key areas of MBR operation that require improvement before the technology can be widely implemented in developing countries. Their findings are summarized in Table 1.1. Their assessment was that MBRs have a good overall sustainability rating, however cost, energy and chemical usage, ease of use, and socio-cultural acceptance need improvement (DiGiano et al., 2004). These areas of need form the motivation for the proposed research.

To date, MBR development has fixated mostly on aerobic systems, which are incapable of recovering energy and instead have large energy requirements due to aeration (McCarty et al., 2011). In addition to energy for aeration, aerobic MBRs use energy for fouling control processes including backwashing, membrane cleaning, and gas sparging of the membrane surface. Fouling control can account for two-thirds of the energy requirements in MBRs (DiGiano et al., 2004). Aerobic MBRs also produce large amounts of biomass from the wasted microbes used to degrade the organic fraction of the wastewater. The production of biomass translates into the need for biomass wasting and disposal of solids from the system. Due to their inherent requirements, aerobic MBRs would be difficult to implement in a slum.

Anaerobic MBRs (AnMBRs) are able to address many of the issues associated with MBRs. When wastewater is treated anaerobically, there is no need for aeration and organic waste can be converted to biogas, which is an energy source that can help offset the energy requirements of the treatment process (McCarty et al., 2011). A study using an AnMBR for domestic wastewater treatment used just a one-tenth of the energy that a typical aerobic MBR would use (Kim et al., 2010). The system effluent, or permeate, usually contains soluble nutrients like nitrogen and phosphorus which can be used to fertilize plants or algae near the point of generation (McCarty et al., 2011). Anaerobic systems also produce significantly less biomass than aerobic systems. Typically, for every kilogram of chemical oxygen demand (COD) removed in an aerobic system, 0.5 kg COD equivalent of biomass is produced, while in anaerobic systems only 0.1 kg COD equivalent of biomass is produced (Khanal, 2009). This means that solids removal occurs much less frequently in anaerobic systems. The membrane process also allows AnMBRs to treat wastewaters with characteristics that would normally overwhelm anaerobic systems including high volume, low-strength wastewaters and on the opposite side of the spectrum, particulate-rich wastewaters (Visvanathan and Abeynayaka, 2012).

1.6 AnMBRs for Urban Slum Sanitation

Unique challenges merit unique responses. International co-operation combined with the transfer and adaptation of innovation can bring about radically new ways of solving problems. Developing countries have used cutting-edge technologies, originating from developed countries, to leapfrog traditional developmental pathways. One example is the use of cellphones in developing countries. By installing cellphone networks, instead of traditional landlines, developing countries like Malaysia have jumped directly into ownership of a world class information and communication network (OECD, 2012). Today, there are almost 6 billion cellphone subscribers globally, which makes them more ubiquitous than toilets (International Telecommunication Union, 2011). The hope is that the same transformative trend can be applied to sanitation systems, whereby new, more sustainable sanitation technologies can be implemented directly into areas where none currently exist. By directly implementing more sustainable technologies, developing countries can bypass the costly and unsustainable infrastructure so common in developed countries. Adapting MBR technology, specifically AnMBRs to meeting the particular challenges of slums settings can allow for this disruptive innovation.

Table 1.1: Sustainability assessment of MBR technology, adapted from (DiGiano et al., 2004).

Sustainability Criteria for MBR Technology (Developed by Bellagio Team using (Balkema et al., 2002) sustainability framework)			
Criteria	Indicators	Improvement needed	Good now
Economic	Cost and affordability	X	
Environmental	Effluent water quality		X
	Microbes		X
	Suspended solids		X
	Biodegradable organics		X
	Nutrient removal		
	Chemical usage	X	
	Energy	X	
	Land usage		X
Technical	Reliability		X
	Ease of use	X	
	Flexibility and adaptable		X
	Small-scale systems		X
Socio-Cultural	Institutional requirements	X	
	Acceptance	X	
	Expertise	X	

Some inherent qualities of AnMBR make them suitable for use in slums. For one, AnMBRs are able to meet the small footprint requirement while being able to handle higher user rates. They are also capable of treating high-strength, particulate-laden wastewaters which are expected from public toilets as they will contain no dilution water coming from appliances and other grey water sources (Liao et al., 2006; Fenner et al., 2007). AnMBRs are better suited to high-strength wastewaters as it increases degradation kinetics and requires less membrane throughput (Liao et al., 2006). Decentralized AnMBRs also allow the possibility of providing treated water that can be used for flushing toilets or for irrigation purposes. This will allow public toilets to be used in water scarce areas. As AnMBRs use membrane filtration, instead of gravity filtration, they can easily be designed to withstand periodic flooding events without compromising treatment goals. Treating waste at the point of generation can help decrease the requirements for solids removal and disposal, which can make the systems more hygienic and can help reduce operating costs. The use of biogas and of solar energy can allow the systems to be energy positive and allow the systems to work in areas that lack a reliable electricity infrastructure. AnMBRs also allow for localized reuse of water and nutrients, thereby decreasing the environmental impact of providing sanitation.

1.7 Research Motivation and Problem Statement

Despite the clear benefits of AnMBRs, they have not been used for sanitation in developing countries. Even within developed countries, the technology is still in its infancy, with most pilots operating exclusively on industrial wastewaters (Lin et al., 2013). This naturally leads to the overarching question of: can a decentralized AnMBR be designed to withstand the harshest of urban environments and function with an acceptable level of reliability[2]? At this moment, there are too many questions and gaps in the literature to adequately answer this question. Knowledge gaps exist in the following key areas:

- The majority of pilot and lab scale studies have been tested with wastewaters that exhibit little variability in terms of composition and strength. This is a result of many lab-scale systems being run on synthetic wastewaters, and pilot systems utilizing wastewaters from centralized treatment plants. However, onsite treatment systems often see much larger fluctuations in these parameters. Exactly how these fluctuations affect AnMBR performance, both in terms of system outputs and filtration performance is yet unknown.
- Biological technologies can be destabilized by changes in operating conditions, yet no AnMBR system has been tested to observe the effects of system disuse. Periods of no flow can be common

[2] Reliability in this case being the probability that a system will perform its intended function for a specified timeframe and stated conditions (Mallory and Waller, 1973). A system's reliability is determined by its robustness, resilience and maintainability. Robustness is defined as a system's ability to handle normal operating and environmental conditions and their associated fluctuations, while not impacting system performance or function. Resilience is defined as a system's ability to return to normal performance or function delivery following unexpected shocks to the system (Blackmore and Plant, 2008). Lastly, maintainability is a measure of the frequency and ease of preventative maintenance and the skill requirements of restoring a system to normal operation following a failure (Mallory and Waller, 1973).

in certain decentralized settings in which wastewater production is seasonal in nature, such as school or hotels.

- While some pilot systems have been operated at fluctuating ambient temperatures, few studies have closely investigated the effect that operating temperature has on the membrane resistance. Understanding the overall impact that such fluctuations can have on system operation is important to minimizing fouling and operator intervention.
- No studies to date have looked at the feasibility of using an AnMBR for complete onsite water recycling on a decentralized basis. It is not known if this process is even theoretically possible, nor if there is enough energy in the wastewater to power the process.
- A completely off-grid AnMBR used for on-site water and energy recovery has not been attempted in the literature, or commercially.

1.8 Research Hypothesis and Objectives

Table 1.2: The Department of Energy's Technology Readiness Level Summary. Adapted from DOE, (2011).

Relative Level of Technology Development	Technology Readiness Level	TRL Definition
System Operations	TRL 9	Full-scale implementation of technology in all relevant environments. A Mature technology
System Commissioning	TRL 8	Full-scale implementation completed and qualified through demonstrations
	TRL 7	Full-scale pilot system in relevant environment
Technology Demonstration	TRL 6	Engineering/pilot-scale system in relevant environment.
Technology Development	TRL 5	Lab scale systems testing
	TRL 4	Component or system validation in lab environment
Research to Prove Feasibility	TRL 3	Analytical and experimental functioning/ Proof of concept
Basic Technology Research	TRL 2	Technology concept or technology formulation
	TRL 1	Basic principles observed and reported

The prospect of improving and adapting the technology to the point where it can "bridge the gap" and be directly implemented for urban sanitation in developing country is what drives this research. This research builds upon previous work at the Membrane Biotechnology Lab of the University of South

Florida, conducted by Dr. Ana Lucia Prieto, which focused on early component and lab-scale systems. Her work concentrated on improving the overall treatment performance and energy balance of lab-scale AnMBRs (Prieto, 2011; Prieto et al., 2013). Using the Department of Energy's Technology Readiness Level (TRL) indicators (shown in Table 1.2), the previous work was conducted at TRL 4 and TRL5 levels. The primary goal of this research is to bring the technology closer to full-scale implementation, by conducting research at TRL6 and TRL7 levels. At these levels, the systems are applied in the actual environments and subjected to the conditions expected at full-scale implementation. Through this research, the following hypotheses will be investigated:

- An AnMBR system can be designed to handle large fluctuations in feed composition and operating temperature while providing a high quality effluent. The system can maintain total COD removal efficiencies above 80% when treating real wastewater, even when subjected to high levels of variability. The membrane will serve as a secondary barrier in the event that the biological performance is compromised by influent or environmental conditions
- AnMBRs are resilient to periods of system disuse. They can return to normal and high levels of COD removal within 1 month after an extended period of disuse. AnMBR system output will not be negatively affected when normal flow conditions are resumed.
- Ambient temperature operation will have a larger impact on membrane performance than previously suggested in the literature. Temperature fluctuations can have a greater impact on membrane fouling than what is described by the temperature correction factors presented in existing literature.
- An off-grid AnMBR can be designed to achieve complete water recycling for a public toilet using only the energy derived from renewable resources onsite, including solar power and the energy content of wastewater.
- An off-grid TRL7 AnMBR can successfully be constructed and operated at the pilot scale to achieve complete water recycling for toilet flushing.

Experiments designed to test these hypotheses were broken down into specific objectives. Objective 1 is to design and construct a TRL 6 AnMBR which would be implemented in a relevant context with the associated variability in temperature and feed composition. This system would serve as a platform for evaluating the treatment performance of an AnMBR when subjected to periods of disuse and fluctuating feed conditions. Objective 2 is to evaluate the effect that operating temperature has on membrane performance when subjected to field conditions.

Objective 3 is to use the experience from the TRL 6 trials to evaluate the feasibility of a full-scale AnMBR used for on-site water recycling. A theoretical mass, energy, and nutrient balance will be performed to assess the feasibility of a TRL 7 system. Information gleaned from objective 3 will be used in the design and construction of a TRL 7 which will be implemented in a high use setting. Objective 4 is the operation of the TRL 7 system in an actual developing country context and the evaluation of its treatment performance during startup and beyond.

1.9 Structure of Dissertation

This dissertation is broken into 7 chapters, with 4 chapters representing the bulk of experimental work. The dissertation structure builds on itself by incorporating data from the earliest experiments into the final design of the TRL 7. Chapter 2 outlines the basic methods and analyses used throughout the studies. Chapter 3 uses a TRL 6 AnMBR to investigate the effects that feed strength fluctuations have on system performance. This chapter also investigates the effects of system disuse, thus achieving objective 1. Chapter 4 assesses the impact that temperature has on membrane performance using a TRL 6 AnMBR. Chapter 5 investigates the feasibility of an off-grid AnMBR coupled to a public toilet using a mass, energy and nutrient balance. Chapter 6 describes the performance of a TRL 7 AnMBR operating in the field for the first 4 months.

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Chapter 2: General Procedures

2.1 Introduction

Research into membrane bioreactors requires a broad assortment of analytical tools and methods ranging from water quality analyses to system control and sensor calibrations. While each individual section contains the specific methods pertaining to that experiment, this section highlights the tools, techniques, and analyses utilized throughout the studies and in the design and construction of the lab and pilot scale systems.

2.2 Water Quality Analyses

2.2.1 Sample Collection and Storage

Liquid samples were pulled directly from sampling ports and kept in glass or polypropylene bottles. Sample containers were prepared prior to collection by triple rinsing with deionized (DI) water. Sample containers were often filled to as close to the lid as possible to minimize volatilization of compounds within the headspace of the sample container. As most of the experiments were conducted far from the lab, samples were stored in zip lock bags and kept out of the sun until during transportation. Samples were analyzed within 1-4 days of sample collection. If the sample could not be analyzed the same day as collection, the samples were refrigerated until they could be processed. Biological testing was always performed within a few hours of sample collection to prevent sample degradation.

For tests conducted in Kerala, samples were routinely collected in disposable water bottles due to the expense and difficulty of obtaining lab grade sample containers. These containers were triple rinsed with DI water prior to sample collection. Due to the lack of refrigeration, all samples from the Kerala pilot were analyzed the same day they were collected.

2.2.2 Chemical Oxygen Demand

Chemical oxygen demand (COD) was used as the primary indicator for the aggregate strength of organics present in wastewater samples. In most experiments COD was divided into two fractions, the soluble fraction (CODs) and total COD (CODt). Raw samples were centrifuged at 3,000 RPM for 20 minutes with the resulting supernatant representing the CODs. COD tests performed on raw samples represented the CODt. Prior to testing for CODt, it was important to vigorously shake the sample container to re-suspend any particulates that had settled out of solution. Transfer of the raw sample into the COD vial was also carefully observed to ensure that no particulate matter was rejected or retained by the pipette tip. With particulate laden wastewaters, pipette tips were cut at an angle to increase the size of the opening, thus avoiding particulate rejection during sample transfer. The primary method used throughout the document was U.S. EPA Standard Method 5220 D. This method was conducted using Hach Company's Test'N'Tube™ Vials Method No. 8000. Due the difficulty of obtaining waste disposal and material acquisition in Kerala, EPA method No. 410.4 was used with locally sourced materials. Three COD standards, 100, 450 and 1000 mg-COD/l, were made using lab grade sucrose and distilled water. These COD standards were then used to make a linear calibration curve of COD and optical density at 420 nm.

2.2.3 Total Phosphorus

Total phosphorus (TP) was tested using Hach Total Phosphorus High Range Test'N'Tube™ vials Method 10127. TP was tested on raw and centrifuged samples to determine the particulate and soluble fractions of TP. Raw samples were centrifuged at 3,000 RPM for 20 minutes and the supernatant was used to determine the concentration of soluble phosphorus.

2.2.4 Total Nitrogen

Total nitrogen (TN) was tested using Hach Total Nitrogen High Range Test'N'Tube™ vials Method 1072. TN was tested on raw and centrifuged samples to determine the particulate and soluble fractions of TN. Raw samples were centrifuged at 3,000 RPM for 20 minutes and the supernatant was used to determine the concentration of soluble phosphorus.

2.2.5 Ammonia

Ammonia testing was conducted using colormetric and ion selective probe methods. The colormetric test used was a salicylate based method using Hach Company's High Range Test'N'Tube^{TM} Method No. 10031. This test was only performed on soluble fractions to prevent interference with particulates. Calibrations and verification of the method was conducted using ammonium chloride based standards. For tests conducted in India, an ion selective probe (Neulog, Rochester, NY) was used for ammonia readings. The probe was calibrated each day prior sample reading. Readings from the probe were taken every 10 seconds for 3 minutes and after a stabilization period of approximately 5 minutes. The average value for those readings was then used as the final value for the sample.

2.2.6 pH, Alkalinity, Turbidity

pH was tested using ion selective probes, which were calibrated and checked on a regular basis. Prior to sample testing, checking the probe's calibration was tested using fresh calibration standards. A weekly three point calibration was often necessary to maintain accuracy of the probes. For anaerobic samples, the pH was often read out after a 2 minute immersion of the probe in the sample. The time limit was set due to a persistent drift that occurred in anaerobic samples, as they equalized with atmospheric conditions. Alkalinity was tested according to standard methods using an ion selective probe to determine the end point pH value. Turbidity was tested throughout the study using a handheld spectrophotometer which was calibrated prior to each sample reading.

2.3 Membrane Filtration Systems

2.3.1 Module Construction

All lab scale modules were constructed in house using Pentair's X-flow tubular membranes. Membranes modules were constructed of PVC with a clear pipe as the primary case to allow the operator to observe macro level changes on the membrane surface. The studies conducted for this dissertation used multiple membrane tubes per module. A polypropylene spacer was fabricated to evenly distribute the membranes within the PVC housing. Three spacers were used, one per end and another for the middle of the module. Once all membranes were in the PVC housing, they were potted in place using a two part epoxy mix. For modules that incorporated biogas scouring, each membrane had a side mounted injection needle to ensure gas delivery to the individual membrane. Previously constructed modules revealed that this was the optimal form of biogas delivery, especially for low biogas scouring rates.

2.3.2 Clean Water Flux Testing

Clean water flux testing was conducted at room temperature (23ºC) and followed after membrane construction or cleaning to determine the baseline performance of the membrane. For these tests, tap water was passed through the membrane using the same feed and permeate pump as the testing skid. Feed side pressure was increased in a stepwise manner by varying the pump setting of the membrane feed pump. A total of five individual settings were used for each clean water flux. Each setting was also tested a total of 3 times. The membrane flux was then divided by the TMP to obtain an average permeability. Often a graph of TMP vs Flux would have to be made to give a better estimate of the permeability at 1 bar (See Figure 2.1 for an example). If the final permeability was within 90% of the manufacturer's permeability value, then the permeability was deemed acceptable. If the permeability was lower than 90%, the membrane module would have to be re-cleaned or discarded.

2.3.3 Membrane Cleaning

Membrane cleaning was conducted using a 500 ppm solution of NaOCl in tap water. This solution was passed through the membrane modules for a total of 10 minutes using the same filtration parameters used during normal filtration. This would be followed by passing the solution in the reverse flow direction (permeate to feed side direction) for 10 mins. The module would then be rinsed with tap water for another 5 minutes. Membrane cleaning would then be followed by a clean water flux test to determine the effectiveness of the cleaning procedure. Membrane cleaning would also be followed by a visual inspection of the membrane surface to inspect for any obvious cake layer still adhered to the membrane surface.

In the rare event that one or more membrane tubes was completely blocked, prior to membrane cleaning, the membrane module would be flushed with a high volume of water in the opposite direction of normal flow (concentrate to feed side) to dislodge any clogged material. Once the membrane was unclogged, a regular membrane cleaning cycle would be commenced.

2.3.4 Membrane Specific Calculations

Below are a few important equations used throughout the study that are not specifically defined in subsequent chapters.

Flux or membrane throughput is calculated with the following equation:

$$J=\frac{Q_p}{A_m} \tag{2.1}$$

where:	J	=	flux (Liters/m^2/hour or LMH)
	Q_p	=	permeate flow (l/hr)
	A_m	=	membrane surface area (m2)

The transmembrane pressure (TMP) is calculated using the following equation for crossflow membranes:

$$TMP=\frac{(P_f+P_c)}{2}-P_p \tag{2.2}$$

where:	TMP	=	transmembrane pressure (bar)
	P_f	=	feed side pressure (bar)
	P_c	=	concentrate side pressure (bar)
	P_p	=	permeate side pressure (bar)

Temperature corrections for the membrane flux were calculated using the following two equations:

$$J_{20}\times\mu_{20}=J_T\times\mu_T \tag{2.3}$$

where:	J_{20}	=	normalized flux at 20^{o}C (LMH)
	μ_{20}	=	viscosity of water at 20^{o}C (cp)

	J_T	=	observed flux at temperature T (LMH)
	μ_T	=	viscosity at water temperature T (cp)

$$\mu_T=1.784-(0.0575\times T)-(10^{-5}\times T^3) \quad (2.4)$$

where:	μ_T	=	viscosity of water at temperature T (cp)
	T	=	water temperature (°C)

2.4 Data Collection and Analysis

2.4.1 Data Collection Components

Automated data collection in the studies was accomplished using ONSET data loggers (Bourne, MA) and a variety of sensors which are described below. The data loggers were powered by AC/DC adapters, but contained their own battery storage in the event of power failure. Data had to be manually readout from the loggers using a USB cable and data logger program (HOBOWare Pro, ONSET, Bourne MA). Readout intervals ranged from a few days to a few weeks depending on the experiment.

2.4.1.1 Wet Tip Meters

Continuous biogas production was measured using Wet Tip Meters (WetTipGasMeters.com). These meters work in the range of 0.5-800 L/d and work by slowly filling a submerged bucket that tips once a set volume has been reached. A magnet on the bucket passes by a magnetic reed switch which serves as a button. For our purposes, the reed switch was connected to a pulse input adapter (S-UCC-M006, Onset, Bourne, MA) which was then connected to the data logger. The input adapter converted the tips of meter into individual events. Each tip would correspond to a discrete volume of gas produced. For data analysis, the biogas volume had to be temperature corrected to account for variations in gas density at fluctuating temperatures. The wet tip meter also had to be manually refilled to maintain the liquid levels during field trials to prevent deviations in the volume per tip.

2.4.1.2 Transducers

The pressure transducers used in this study were series EW-68075-32 Cole-Parmer pressure transmitters with a -14.6 psi to 15 psi range. The transducers required an excitation voltage of 24 volts DC and required a millivolt adapter to connect to the data logger. For most skids, a standard AC/DC wall adapter was used to provide power for the transducers. In the Kerala study, a 24 volt power adapter was installed to minimize the voltage fluctuations observed in the battery bank. The transducers were calibrated using a short closed segment of PVC tubing connected to pressure gauge and syringe. The syringe was used to vary the pressure inside of the PVC segment. The transducers were calibrated using the voltage reading of the transducer at 5 different pressure ranges. A linear calibration was then used throughout the study.

2.4.1.3 Permeate Flow and Rain Gauges

The initial studies used commercially bought, rain gauges for determining permeate production rates. These tip based meters used a small bucket that tipped back and forth to trip a reed switch. Electrical pulses from the reed switch could then be used to estimate volume. Rain gauge calibrations were conducted using a high precision pump. The pump was used to provide a constant flow into the rain gauge. The number of tips per minute could then be used to calculate the average volume per tip. The accuracy of rain gauges drifted over time, and due to the small volume per tip, the error associated with this method was high. To prevent inaccurate calculations, the rain gauges were calibrated once a week and were often compared to periodic measurements of permeate flow using a graduated cylinder and stopwatch.

2.4.1.4 Flow Meters

Liquid flow was monitored using paddlewheel flow meters (FB151 Series, Omega Engineering, Stamford, CT) which operated on a 4-20 ma current circuit. Each sensor had to be independently powered, so a 12 volt 7 ah battery was connected in series to all of the sensors. Power for this battery was maintained by a 12 volt 0.5 amp solar panel connected to a charge controller. The circuit was then connected to a milliamp adapter (S-CIA-CM14, ONSET, Bourne, MA) for signal conditioning prior to input into the data logger. The flow sensors came with calibration values that were validated by manual measurements.

2.4.1.5 Temperature

Temperature was monitored using thermocouples (S-TMB-M006, Onset, Bourne, MA). Although the sensors came pre-calibrated, the readings were validated with boiling water prior to use. Two sensors were used to measure reactor temperature to account for any temperature gradients. The temperature sensors were placed at the top and bottom of the reactor. The average of the two values was used when reporting reactor temperature. The probes were potted in PVC pipe segments, which were then fitted directly into the reactor vessel. Influent temperatures were measured with a single sensor on the main lines entering the reactor. Ambient temperatures were measured using a single point within the housing structure.

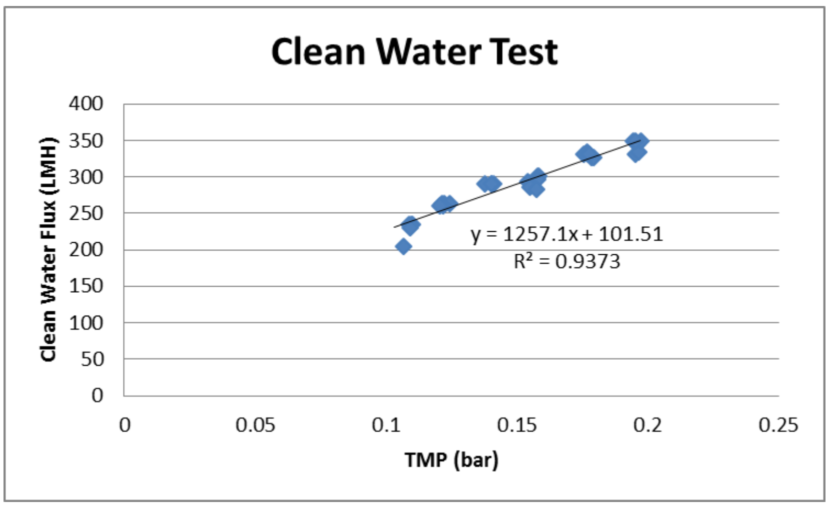

Figure 2.1: Example of a clean water test result used to predict the permeability at 1 bar.

Chapter 3: Long Term Performance of an Anaerobic Membrane Bioreactor (AnMBR) Treating Domestic Wastewater: Effects of Variable Feed Strength and Intermittent Operation

3.1 Introduction

Despite the numerous advantages of anaerobic membrane bioreactors (AnMBR), few full scale examples of their implementation exist for domestic wastewater treatment (Skouteris et al., 2012; Smith et al., 2012). Much of recent AnMBR research on has focused on making systems suitable to low-strength wastewater by improving membrane flux, decreasing the hydraulic retention time (HRT) and reducing the energy requirements of membrane filtration (Ozgun et al., 2013; Skouteris et al., 2012; Smith et al., 2012). Improvements in these specific areas are necessary to use the technology as a replacement for centralized treatment where low strength wastewaters are common. However, there are examples of their successful use for high-strength industrial wastewaters treatment (Christian et al., 2010; Grant et al., 2008; Kanai et al., 2010). With industrial wastewater, the energy density is more than sufficient to offset the energy required for treatment (Kanai et al., 2010). Industrial systems also deal with smaller volumes, where low membrane flux can be compensated by increasing the total amount of membrane area.

There are specific locations in the existing sanitation chain where high strength and relatively low volume wastewaters can be found. Examples of these locations include water-efficient buildings, public toilets, and fecal sludge coming from septic tanks and pit latrines. In cases like fecal sludge management, wastewaters can have concentrations above 10,000 mg-COD/L which makes it higher than many industrial wastewaters (Koné & Strauss, 2004). Higher strength domestic wastewater is also more common in developing countries, where lower per capita water usage prevents wastewater dilution (Mara, 2013). Onsite application of AnMBRs at these specific points in the sanitation chain would result in high strength wastewaters, since the treatment system is closer to the point of generation (Tchobanoglous et al., 2014). Decentralized treatment also benefits from reduced inflow and infiltration rates due to the reduced size of their collection system (Tchobanoglous & Leverenz, 2013).

However, decentralized treatment can be challenging as influent concentrations and flow rates have greater variability due to a decreased dampening effect by the smaller collection system (Butler & Graham, 1995). Peaking factors, which describe the flow variability experienced by a treatment plant, can be predicted by equation 3.1 (Mara, 2013). As can be seen, the peaking factor can significantly increase when lower populations are served.

$$PF=14P^{-1/6} \tag{3.1}$$

where PF is the peaking factor and P is the population served by the system. Almeida et al., observed large hourly fluctuations in COD content of when studying wastewater composition at the house hold scale (1999). At such a decentralized level, each appliance or toilet use can have a significant impact on the wastewater composition, which can fluctuate substantially throughout the day (Almeida et al., 1999). Yet, most lab and pilot scale AnMBRs are operated with wastewaters that exhibit very little variability. Table 3.1 shows the influent wastewater characteristics for a few lab and pilot scale AnMBRs that were operated with real wastewater. The coefficient of variation (CV), an indicator of the variability of wastewater COD value is also shown in the table. Many other AnMBR studies have used synthetic wastewater where the variability of the feed is even lower. Understanding the robustness of AnMBRs to fluctuations in feed composition will allow engineers to properly design them for decentralized applications.

Certain decentralized applications present the challenge of having seasonal patterns and periods when flows can drop to zero (Abegglen et al., 2008). These locations can include hotels, schools and other facilities where AnMBRs could be applied. If the period of disuse is prolonged, the biological system may go dormant and may need an additional startup time. The purpose of this research is to determine the applicability of a decentralized AnMBR for treating wastewater of various strengths close to the point of generation, testing its ability to handle large variations in influent strength and the effects of long periods of no flow.

Table 3.1: Wastewater strengths and variability of lab scale and pilot scale systems treating domestic wastewater. References: [1] Gimenez et al., (2011); [2] Pretel et al. (2014); [3] Smith et al. (2013). In reference No. 3, two operational periods are reflected.

Ref.	WW Type	WW Strength (mg-COD/L)	Std. (mg-COD/L)	Coefficient of Variation (%)
[1]	Domestic WW	445	95	21.35
[2]	Domestic WW	650	147	22.62
[3]	Domestic WW	440 259	68 82	15.45 31.66

3.2 Materials and Methods

3.2.1 AnMBR Configuration

The reactor for this study (Figure 3.1) consisted of a 20 liter AnMBR designed to treat wastewater at ambient temperatures. The design consisted of two sequential reactors, with the first reactor operating as an upflow anaerobic sludge blanket (UASB), and the second reactor being completely mixed due to the return flow of a coupled side stream membrane filtration unit. The two reactors were of equal volume (10 liter liquid volume) and contained a total of 500 ml of floating polyethylene media (Kaldnes Media) with 0.425 m^2 of surface area. The media was added to allow for attached growth and biological resilience. The reactors were insulated with a layer of foil-faced bubble wrap to minimized large temperature swings, but were not provided with additional heating.

Two membrane modules were used for this study. One membrane module contained three 5.2 mm in diameter, tubular ultrafiltration membranes (X-flow modules, Pentair) made out of polyvinylidene fluoride (PVDF) with an average pore size of 0.03 µm. This membrane unit, labeled M1, contained 0.0163 m^2 of membrane surface area. The second membrane module, labeled M2, contained larger 8 mm tubular membranes with a total surface area of 0.026 m^2 of the same material and pore size as M1. Both membrane modules were run in parallel and fed with the contents of Reactor 2 which was pulled from the top of the reactor. The first 80 days of operation used gas-lift as the sole membrane feed mechanism.

Biogas from the head space of both reactors was injected into the bottom of each membrane module at a rate of .1 LPM resulting in a crossflow velocity (CFV) of 0.1 m/s for the 8mm module and 0.2 m/s for the 5.2 mm module. After 80 days, a dual head peristaltic pump was added to the system to serve as an additional membrane feed pump. This pump was set to maintain a similar CFV as achieved during the gas lift phase. The concentrate from both membrane modules was separated in a gas/liquid separator before returning to the bottom of Reactor 2. Permeate was extracted using a variable speed peristaltic pump on the permeate line of both membranes. The membrane modules were backwashed at 25 LMH for 15 seconds every 45 minutes. The AnMBR was operated at a membrane flux below 5 LMH during all four phases. Although the membranes were capable of higher fluxes, a low flux was maintained to prolong the period between cleanings. Both modules' TMP and flux were allowed to fluctuate throughout the trial.

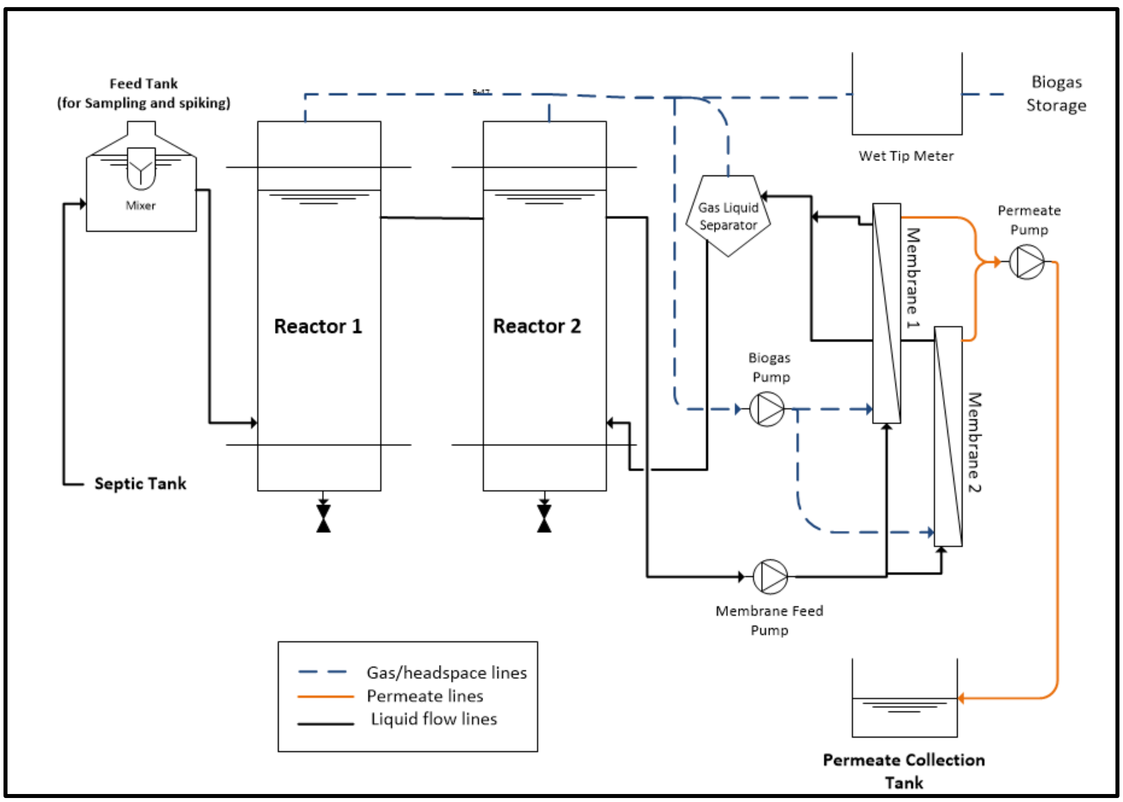

Figure 3.1: Schematic of the pilot AnMBR used for this study.

3.2.2 Inoculation

The AnMBR was inoculated with mesophilic digester sludge obtained from a local wastewater treatment plant (Howard F. Curren Advanced Wastewater Treatment Plant, Tampa, Fl.). The sludge was screened with a no. 20 sieve to remove large particles and waste solids prior to inoculation. Both reactors were inoculated with 6 liters of sludge with a total suspended solids (TSS) concentration of 20.6 ± 0.2 g/l and a volatile suspended solids (VSS) concentration of 14.8 ± 0.1 g/l. The reactor was fed with wastewater obtained from a local elementary school's septic system (Learning Gate Community School, Lutz, Fl.) after a grinder station and prior to entering the septic tank. A submersible pump with a 2 mm screen over it was placed directly in the grinder station and provided fresh sewage to a 30 liter feed tank. The feed tank was mixed every minute for 30 seconds to keep particulate matter suspended. Sewage pumping and reactor levels were controlled by float switches and time delayed relays.

3.2.3 Chemical Assays and Sampling

Liquid samples were collected from the Feed Tank, Reactor 1, Reactor 2 and permeate lines every 3 days. The sampling point for Reactor 1 was above the sludge blankets, which signifies that only the supernatant of the reactor was tested. Biogas samples were pulled directly from the headspace of the reactor using Tedlar gas bags. Temperature, pressure, permeate, and biogas production were continuously monitored using data loggers (ONSET, Bourne, MA). Pressure was monitored using transducers (Cole-Parmer, Vernon Hills, IL) located on the feed, concentrate and permeate side of each membrane unit. Biogas was monitored using a wet tip meter while permeate was measured using a low-flow permeate meter.

Turbidity, TSS, VSS, pH, and Alkalinity were analyzed on the liquid samples using tests described in Standard Methods (2005). COD and nutrient tests including NH_4^+, PO_4^{3-}, and total nitrogen (TN), were conducted using HACH digestion vials (HACH Company, Loveland, CO). Soluble COD (CODs) and soluble nutrient values were obtained from the supernatant of raw samples that had been centrifuged at 3,000 RPM for 20 minutes. The particulate fraction COD (CODp) was calculated by subtracting CODs from the total COD (CODt). The biogas composition was tested using an isothermal method on an Agilent 7280a Gas Chromatograph (GC) (Agilent Technologies, Santa Clara, CA) equipped with a flame ionization detector (FID) and a Nukol 0.25μm capillary column (Sigma-Aldrich, St. Louis, MO).

3.2.4 Experimental Plan

The system was operated for a total of 365 days starting in summer. It was operated in seven distinct phases each done to simulate different applications of AnMBRs as well as to test the system's ability to hand discontinued use. What follows is a description of the operational conditions of each phase as well as the rationale behind it.

3.2.4.1 Phase 1

This phase was conducted after a 15 day initial startup period in which the anaerobic microbial consortia stabilized as determined by biogas production (the startup phase is not included in the data set). During Phase 1, the reactor was fed pre-screened wastewater directly from the school's grinder station. The wastewater had an average concentration of 185 ± 146 mg/L COD with high daily variation. The organic loading rate (OLR) was maintained at around 0.10 g-COD/L-day. This phase lasted for approximately 20 days during which the average daily temperature was 30^{o}C.

3.2.4.2 Phase 2

This phase was conducted to simulate high strength domestic wastewater. This 35 day period used wet dog food (Alpo, USA) to boost the COD content of the school's wastewater. The dog food was homogenized using a blender for 1 minute before being added to the feed tank. The target influent COD concentration during this stage was 1000 mg/L COD. The average organic loading rate during this stage was 0.20 g-COD/l-day. The average daily temperature during this phase was 30^{o}C.

3.2.4.3 Phase 3

Phase 3 mimicked high strength wastewater from onsite blackwater treatment, as can be expected from public toilets common in slums (Fenner et al., 2007). In these locations, dilution water from graywater sources is minimal resulting in very high strength wastewaters. This 55 day period used the same dog food and method of spiking as phase 2 to boost the COD content of the school's wastewater to a target COD concentration of 4000 mg/L. The average organic loading rate during this stage was 0.76 g-COD/l-day with an average daily temperature of 26.5ºC. It was during this phase that the membrane feed pump was installed.

3.2.4.4 Phase 4

This phase used wastewater that imitated fecal sludge pits where only the water introduced is from anal cleansing and only 1 liter of water is used for flushing (Fenner et al., 2007). Dog food was added to the school's wastewater to increase the COD concentration to the target of 10,000 mg/L. The average OLR increased to 1.33 g/L-day due to the higher COD loading. During the phase the average ambient temperature started dropping, resulting in an average daily temperature of 23ºC.

3.2.4.5 Phase 5

During this 80 day run, we subjected the system to high variations in the influent feed strength. This was done to test the system's ability to cope with high feed strength variability, which is expected in decentralized settings. The incoming COD concentrations were varied between 1000 to 7313 mg/L –COD during this phase. The OLR during this period was kept within a range of 0.02 to 4.63 g/L-day while the average temperature was 20ºC.

3.2.4.6 Phase 6

This phase was an intentional shut down of the system for 55 days. During this shut down, the membrane feed pump was turned off and all influent pumps were turned off. This was done to simulate how the reactor would handle periodic shutdowns, which can occur in many locations such as schools and hotels which have seasonal shifts in wastewater production.

3.2.4.7 Phase 7

This phase resumed operation of the AnMBR after the shut-down period and was done to test how quickly the system recovered from prolonged pauses in operation. This phase was started using the school's wastewater for the first 30 days. However, due to the dilute nature of the wastewater, the influent was spiked to a 1225±225 mg/L-COD after the first 30 days. In total, this phase lasted 100 days. The average temperature during this time was 24°C and the average OLR was 0.44 g/L-day. During this time the sample collection rate was decreased to once every week.

3.3 Results and Discussion

3.3.1 AnMBR Performance

The performance of all seven phases can be found in Table 3.2. The average CODt removal over all seven phases was 89.4% with a CODs removal of 78.2 %. As can be observed in Figure 3.2, the lowest COD removal rates occurred in phase 1, which also had the lowest incoming COD concentrations. During this phase, there were days in which the influent CODt concentrations were below 100 mg/L, of which little was readily biodegradable, resulting in low COD removal rates. However, during Phase 1, permeate COD values never rose above 65 mg/L and had a low average turbidity value of 3.8 NTU. Low incoming wastewater characteristics are a result of high dilution water and lower defecation rates that are typical of elementary schools. Phase 3 and Phase 4 had high removal efficiencies of over 95% CODt and 93% CODs. These high removal efficiencies were obtained at ambient temperatures and with high incoming wastewater concentrations. Near the end of phase 4, the ambient temperature dropped down to as low as 19°C, which can explain the decreasing removal efficiency observed at the end of Phase 4.

Despite high variation in incoming wastewater strengths, the CODt removal efficiency remained above 80% throughout most of Phase 5. This is despite the steadily decreasing average temperature range during this same period. There was however one point during which the removal efficiency dropped below 70%. This instance occurred when transitioning from an influent concentration of 3000 mg/L-COD to 1000 mg/L-COD. The lower treatment efficiency during this transition can be explained by the residual breakdown of material accumulated in the reactor during the higher feeding interval. As the materials degrade, a portion of CODs is able to pass through the membrane resulting in high CODs concentrations in the permeate. When restarting the AnMBR after the prolonged shut-down period, the CODt removal efficiency was below 50% for the first 14 days and did not go above 70% until after 30 days. However, during this time, the system was fed wastewater with COD concentrations below 200 mg/L, making it difficult to achieve removal efficiencies above 70%. After spiking the incoming wastewater, the removal efficiency immediately increased to above 95% and remained above 85% for the remainder of Phase 7.

Table 3.2: Summary of treatment performance during phases of operation. Phase 6 not shown due to inactivity.

	Phase 1			Phase 2			Phase 3			Phase 4			Phase 5			Phase 7		
Parameter	In	Out	% Removal	In	Out	% Removal	In	Out	% Removal	In	Out	% Removal	In	Out	% Removal	In	Out	% Removal
CODt (mg/l)	185.0	44.3	76.0	311.0	66.9	78.5	1068.7	108.9	89.8	8854.0	334.1	96.2	3330.0	140.3	95.8	920.9	84.9	90.8
CODs (mg/l)	132.0	44.3	66.4	311.2	66.9	78.5	1420.4	108.9	92.3	4649.4	334.1	92.8	835.9	140.3	83.2	415.0	84.9	79.5
Turbidity (NTUs)	141.8	3.8	97.3	801.4	4.1	99.5	1652.9	15.0	99.1	3418.5	54.9	98.4	1496.7	59.8	96.0	430.7	4.2	99.0
NH4 (mg-N/l)	42.9	81.8	-90.6	98.7	98.5	0.2	194.3	191.7	1.3	471.5	341.4	27.6	113.2	125.1	-10.5	57.9	77.1	-33.2
TN (mg-N/l)	42.6	76.1	-78.5	144.0	106.7	26.0	319.4	194.0	39.2	729.2	412.6	43.4	151.4	106.2	29.8	65.9	63.4	3.8
TP (mg-P/l)	9.7	11.0	-13.7	20.9	12.9	38.4	50.7	16.6	67.3	103.6	28.2	72.8	21.0	11.5	45.5	14.7	7.3	50.8

Biogas production, summarized in Table 3.3, increases with increasing feed strengths and OLRs. Small leaks in the headspace prevented comprehensive biogas measurements and occurred during the initial half of Phase 2 and Phase 4. Biogas production rates were strongly related to ambient temperatures, with biogas generation being lowest before dawn and highest a few hours after mid-day. This trend can be seen in Figure 3.3. Particulates and soluble COD retained by the membrane accumulated during the night and were degraded when the temperature increased during the day. The diurnal temperature swings, which can be expected from reactors run at ambient temperatures, did not adversely affect the reactor stability or overall treatment performance. During the 365 days of operation the reactors remained stable in terms of pH and alkalinity without additional buffering. Stable pH was maintained even when the feed pH decreased to 5.5, which was observed at higher feed concentrations. The low pH values observed in the feed tank were a result of biological activity occurring within the feed tank. The system stability is summarized in Figure 3.4.

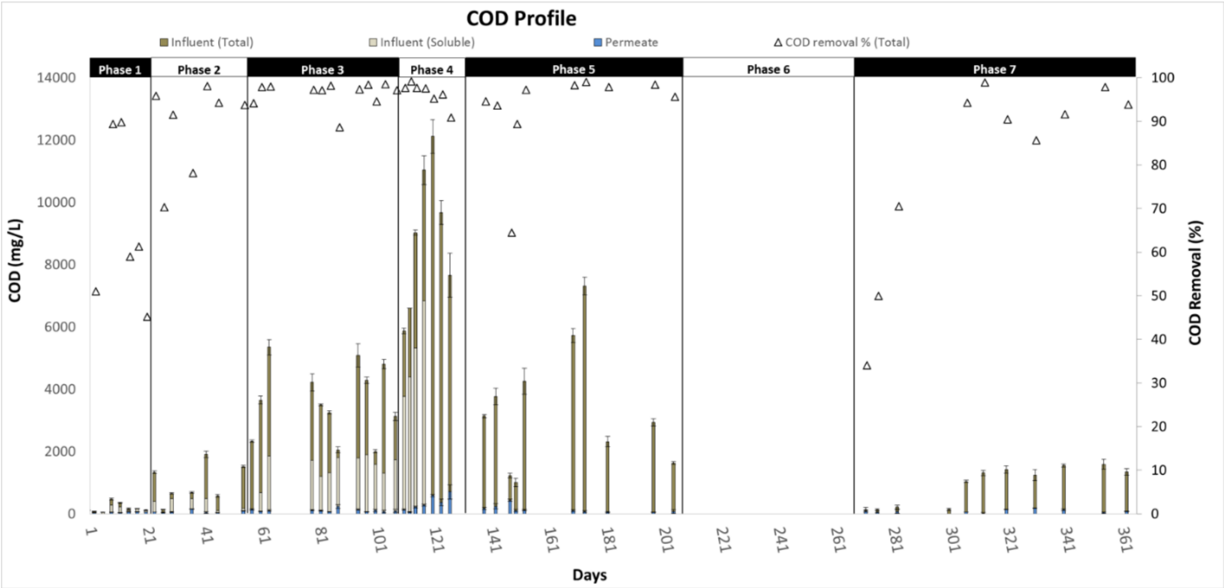

Figure 3.2: COD Profile during all seven phases of AnMBR operation. Bars are overlapping each other.

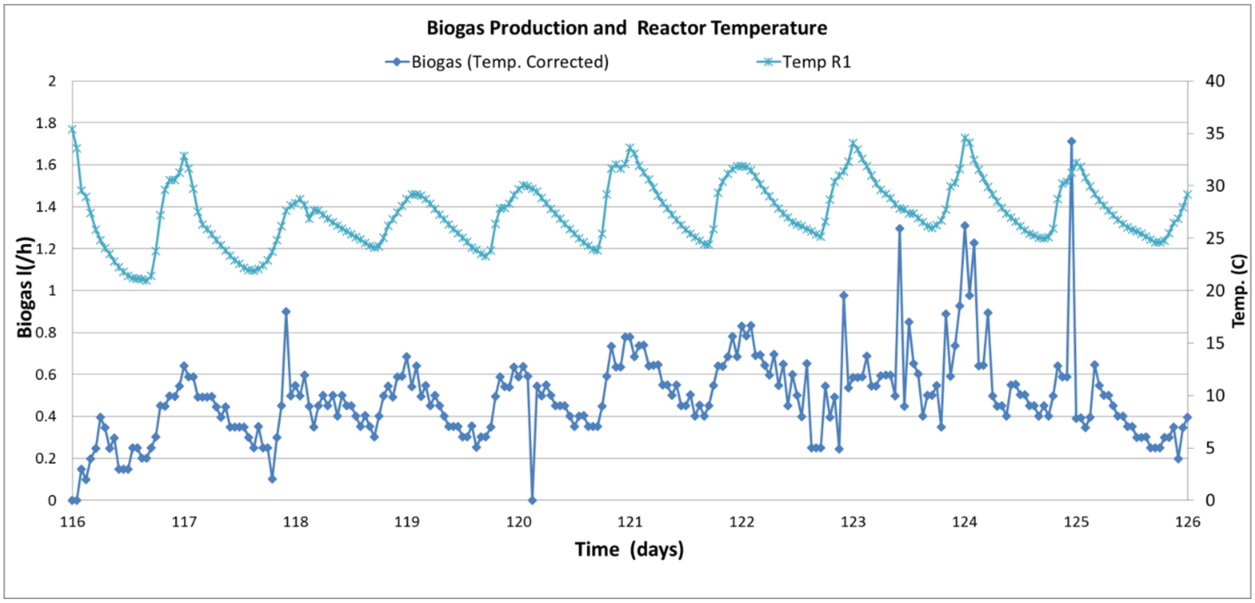

Figure 3.3: Close up of average ambient temperature and daily biogas production. This short interval highlights the impact of diurnal temperature swings on biogas production.

Table 3.3: Average biogas and OLR for all 7 phases.

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7
Biogas Production Ave. (l/d)	0.05 ± 0.22	0.37 ± 0.82	4.92 ± 3.9	6.72 ± 5.75	2.37 ± 1.69	1.42 ± 1.56	0.72 ± 0.63
Biogas Production Corrected For 25°C (l/d)	0.04 ± 0.21	0.21 ± 0.71	4.84 ± 3.86	6.66 ± 5.71	2.39 ± 1.69	1.43 ± 1.56	0.72 ± 0.75
Organic Loading Rate (g COD/l.d)	0.10 ± 0.07	0.20 ± 0.14	0.76 ± 0.76	1.33 ± 0.79	1.48 ± 1.28	0	0.44 ± 0.44

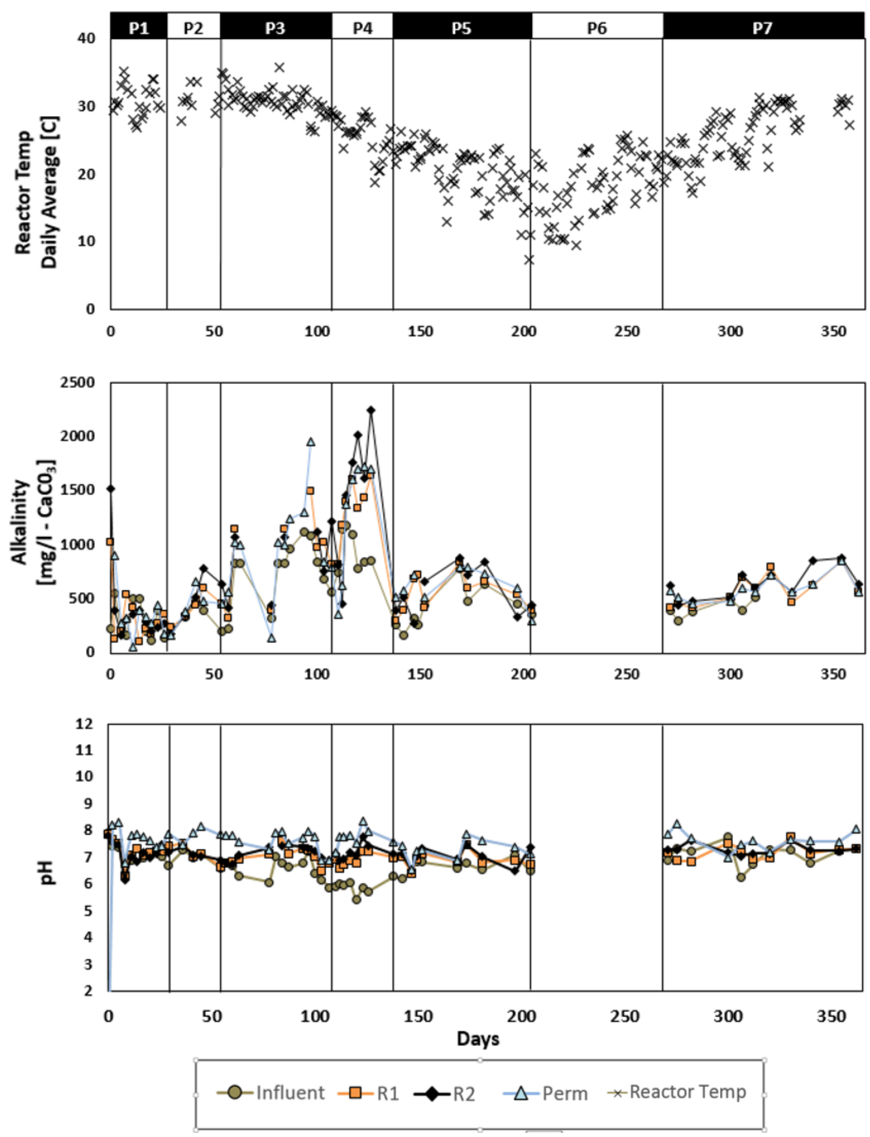

Figure 3.4: Reactor temperature and stability over the four phases. Reactor stability is indicated by pH and alkalinity values.

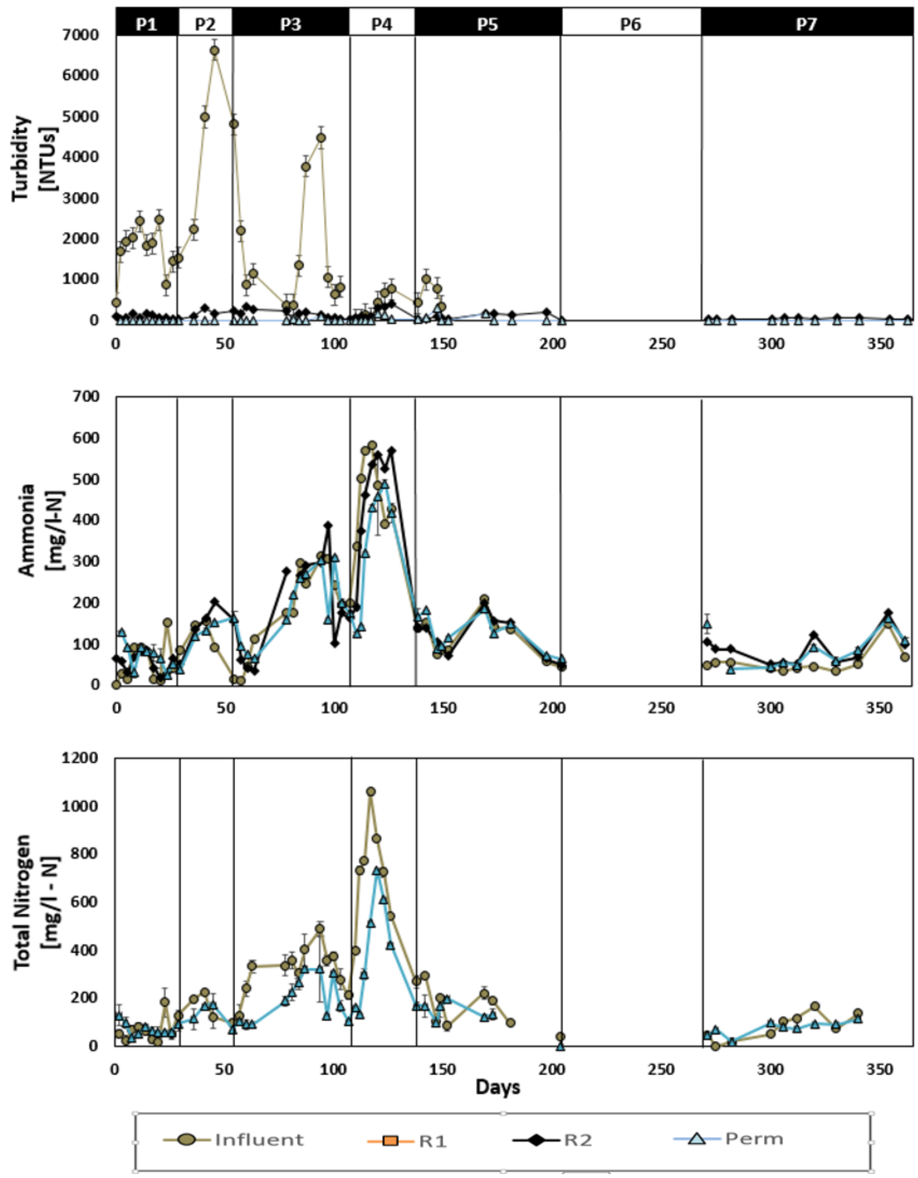

Figure 3.5: Nutrient values and turbidity values for all four stages of operation.

Biofouling was minimized using biogas sparging and the periodic backwashing as previously described. The flux of both membrane modules decreased when feed concentrations increased and with lower ambient temperatures. Nutrients such as nitrogen and phosphorus fluctuated with the incoming feed concentration. Nutrient concentrations in the feed and permeate are summarized in Table 3.2 and can be seen throughout the operation in Figure 3.5. At the highest feed COD concentrations the ammonia levels went above 500 mg/L – N, yet there was no evidence of ammonia inhibition at these concentrations. As can be expected from anaerobic digestion, the nitrogen and phosphorus levels were not significantly reduced during the process.

3.3.2 Discussion

Decentralized treatment systems need to have a high degree of reliability, meaning that they are able to perform their desired function (wastewater treatment) to a high standard despite changing conditions and internal system failures. Decentralized systems need to be highly reliable because of the consequences of system failure, which includes exposing the public to pathogens. A system's overall reliability depends the system's resilience, robustness, and redundancy. Resilience refers to the system's ability to recovery or adapt to changing conditions, while robustness refers to a component's ability to be unaffected by changing conditions. If a component is neither robust nor resilient, it can be made redundant to minimize the effect of its eventual failure. With AnMBRs, the membrane enhances the system's resilience by ensuring that beneficial microbes, pathogens, and contaminants do not leave the system through the permeate even when the biological component of the system has been compromised. This can be the case when the HRT is suddenly lowered, after a shock loading, and/or after a prolonged period of inactivity. In this way AnMBRs are superior to traditional septic tanks and latrines, which can have washouts in the event of any biological perturbation. Taken together, the results of the previous experiments point towards the system's overall reliability under conditions that can be expected in decentralized conditions.

As seen in Figure 3.6, the system had higher overall CODs removal rates when treating higher levels of incoming CODt. However, the removal rate of CODt was fairly consistent throughout all phases of operation. This can be explained by the high removal rates of particulates, which represented a significant fraction of the CODt. As was discussed earlier, it is possible to have higher strength wastewaters from domestic sources by limiting the amount of gray water that enters the collection system. In addition, the less wash water makes its way to the waste stream, the lower the wastewater flow that will need to be treated. A benefit to treating higher strength wastewaters with lower flow rates is that the HRT of a system can be longer for reactors of identical volumes. Systems with longer HRTs result in more reliable treatment of complex organics as they are less inclined to destabilization or acidification (Rincón et al., 2008). Lower volumes also allow the system to be operated at lower fluxes (assuming identical membrane surface area), which can prolong the time between cleaning and decrease membrane fouling (Judd, 2010). Longer HRTs can possibly reduce fugitive methane emissions by allowing the biogas to equilibrate with the reactor headspace, instead of being pulled out with the permeate at supersaturation concentrations (Smith et al., 2013). This can improve energy recovery as well as prevent harmful greenhouse gas emissions. As the technology stands, it should be suitable to handle the higher incoming feeds strengths and OLRs that are found in areas like fecal sludge, public toilets, and water efficient buildings.

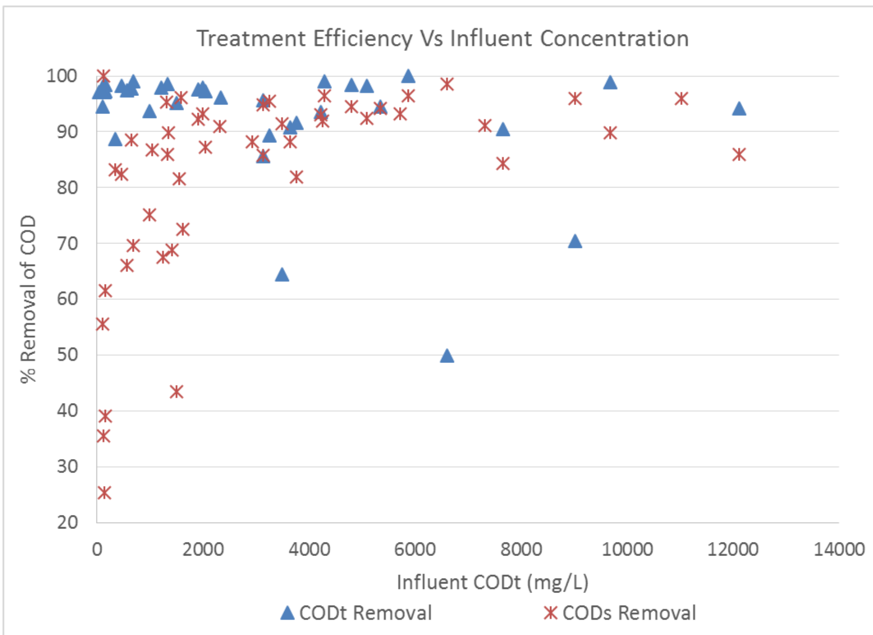

Figure 3.6: CODs and CODt removal efficiency as they relate to incoming CODt concentrations. This graph includes all testing phases.

While wastewater strengths tend to increase the closer they are obtained to the point of generation, the amount of variability both in terms of composition and volume also increases. Systems that are directly coupled to houses or public toilets do not benefit from the buffering provided by a collection system, so their flow and composition variations can be extremely high. Fluctuations in flow can be reduced with equalization tanks, however controlling for the influent strength is a greater challenge. As can be observed in phase 5, the AnMBR had a reliable biological performance even during high influent strength variations. This is a promising result, indicating that the systems are able to perform in these decentralized locations.

In some decentralized locations where AnMBRs might be applicable, wastewater production might be seasonal in nature. Lengthy shut down periods can be followed abruptly by high wastewater production. This can be the case in institutions that close seasonally, like schools, or areas that depend on the seasonal influx of tourists or migrant workers, such as hotels, construction sites or farms. With aerobic systems, the biomass must be maintained, even during shutdown periods, with some form of aeration. That translates into an energy demand even when no wastewater treatment is occurring. As was determined in phase 6 and 7, AnMBRs can be left for long periods being completely shut down. When the wastewater production resumes, a very short period of time is required before the system can resume normal operation. The ability to rapidly restart AnMBRs after prolonged periods of inactivity make them useful for decentralized locations requiring seasonal waste treatment.

3.4 Conclusions

A pilot scale AnMBR was fed a variety of wastewater strengths ranging from 185 – 8854 mg/L COD at ambient temperatures to mimic a variety of wastewater sources. This system was then subjected to large fluctuations in feed strength to resemble the variably observed in decentralized wastewater treatment systems. Lastly, the system was left inactive and restarted to understand how system inactivity and rapid startup affects system performance. The following conclusions were made based on the observations of the system:

- For all of the incoming feed strengths, the system was able to attain CODt removal efficiencies of over 89.4%. The system did perform better when treating higher strength wastewaters, attaining COD removal efficiencies above 95%.
- High removal efficiencies were possible even with daily and seasonal temperature fluctuations.
- COD removal efficiencies remained above 70% during high daily feed concentration variations.

- After a prolonged shutdown period, the AnMBR was able to recover its treatment efficiency in less than 30 days of operation.

Together, these results suggest that there are many locations in the existing sanitation chain that are well suited for the application of AnMBRs. Public toilets, fecal sludge treatment facilities, and water efficient buildings are all locations which have higher feed strengths. As the technology stands, it should be able to handle the higher incoming feeds strengths, variability, and seasonality that is common at these decentralized locations.

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Chapter 4: Ambient Temperature Fluctuations and Their Impact on Fouling Resistance

4.1 Introduction

Temperature is a critical operational parameter that is known to affect biological wastewater treatment technologies. In particular, anaerobic microbial consortia are known to be sensitive to changes in operating temperatures (Choorit & Wisarnwan, 2007; Gao et al., 2011; Sanchez et al., 2001). As domestic wastewater temperatures can vary greatly depending on location and season, with temperatures often dropping below optimal mesophilic and thermophilic temperature ranges, understanding the effects that low temperatures have on operation is critical for widespread implementation of anaerobic technologies. Temperature fluctuation is of great concern for decentralized treatment technologies, as variability increases when extensive collection systems are not present to dampen and homogenize flows (Campos & Von Sperling, 1996; Von Sperling, 2007). What is known is that biologically mediated processes tend to slow down at lower temperatures. This is partially due to a decrease in reaction rate kinetics, lower growth rates, lower substrate utilization rates, and changes in equilibrium constants experienced at lower temperatures (Lettinga et al., 2001; Metcalf & Eddy, 2014).

Studies found that the effects on treatment performance at lower temperatures can be reduced by an acclimatization regime, whereby the microorganisms are slowly adapted to the lower temperatures, and by changes in reactor operation, including increasing the solids retention time (SRT) (Lettinga et al., 2001). However, depending on the microbial makeup of the reactor, acclimatization can be a slow process, and there is the possibility that large temperature and flow variations can cause disruptions to an acclimatization regime. These types of shocks and variability are a greater concern for decentralized systems which can also lack the careful monitoring required for changes in reactor operations to deal with fluctuating temperatures. Yet another option is to heat the anaerobic reactor, which allows for greater biological stability. While this solution is appealing in its simplicity, it substantially increases the energy required for treatment, rending anaerobic treatment of dilute wastewaters energetically unfavorable (Smith et al., 2013).

Membrane technologies offer one potential solution to treating dilute wastewater flows that experience temperature fluctuations. In particular, anaerobic membrane bioreactors (AnMBRs) which combine anaerobic treatment with membrane filtration, allow for complete retention of particulates and a fraction of soluble macromolecules within the reactor (Judd, 2010; Smith et al., 2012). Additionally, they are able to decouple the SRT from the hydraulic retention time (HRT), thus allowing slow growing anaerobes to be retained within the system, even during challenging low-temperature, high flow conditions (Chu et al., 2005). Previous studies, including Smith et al., have shown satisfactory chemical oxygen demand (COD) removal using an AnMBR at psychrophilic temperature ranges (2013). Other studies observed similarly high COD removal rates during low temperature conditions using an AnMBR, but observed that the membrane's ability to retain soluble COD plays a large role in the total COD removal rates at low temperatures (Chu et al., 2005; Wen et al., 1999). However, just as biological processes are affected by temperature, membrane filtration can also be affected by temperature. Membrane permeability is known to decrease at lower temperatures and is accounted for within the industry with a temperature correction factor (USEPA, 2005). When membrane flux is maintained constant, the following two equations can be used to determine temperature dependent changes in the transmembrane pressure (TMP).

$$TMP_{20}=TMP_{T}\left(\frac{\mu_{20}}{\mu_{T}}\right) \tag{4.1}$$

where TMP_{20} is the transmembrane pressure at 20°C, TMP_{T} is the transmembrane pressure at temp T (°C), μ_{20} is the permeate viscosity at temp 20°C, and μ_{T} is the viscosity at temperature T (Cp).

$$\mu_{T}=1.784-(0.0575\times T)+\left(0.0011\times T^{2}\right)-(10^{-5}\times T^{3}) \tag{4.2}$$

where μ_{T} is water viscosity at temperature T (Cp), and T is temperature in °C.

As can be seen with these two equations, the changes in TMP as they relate to temperature are primarily dependent on changes in permeate viscosity, which increase at lower temperatures. Using the two equations shows that changes in viscosity can lead to an increase of TMP by up to 31% when the temperature drops from 20ºC to 10ºC. However, these equations only account for the changes in the permeate viscosity within a small temperature window. When membrane filtration is combined with a biological process, there are many more interactions and mechanisms that can affect the filtration process. Van den Brink et al. when observing a full-scale aerobic membrane bioreactor (MBR) noticed seasonal variations in membrane permeability that were closely linked to temperature (2011). The effect that temperature had on membrane permeability was much greater than that predicted by the membrane temperature correction factor. In the case of that study, the membrane flux decreased by 50% more than predicted by temperature correction models (van den Brink et al., 2011). An increase of that magnitude can have hefty implications on the total energy required for wastewater treatment. Additionally, much of recent AnMBR research has focused on membrane fouling and mitigation, yet it seems that temperature fluctuations can have similar effects on membrane performance as that of severe fouling.

While some studies have investigated the effect that temperature has on aerobic MBRs, few studies have investigated their effects on AnMBRs. Even then, most lab studies focus on a slow and constant ramping up or down of temperature rather than looking at how cyclic fluctuations affect membrane performance. Others focus almost exclusively on the impact that fluctuations have on the biological performance (Gao et al., 2011). What is not fully understood is how membrane performance is affected by the interaction of anaerobic treatment when experiencing diurnal temperature fluctuations, as would be expected in decentralized AnMBR systems.

4.2 Materials and Methods

4.2.1 Reactor Design

The reactor for this study (Figure 4.1) consisted of two sequential anaerobic reactors followed by membrane filtration. The first reactor was operated as an upflow anaerobic sludge blanket (UASB), while the second reactor was completely mixed due to the return flow of two side-stream membrane modules.

The two reactors were of equal volume (10 liters liquid volume) each containing 500 ml of floating polyethylene media (Kaldnes Media) with 0.425 m^2 of surface area. The media was added to contribute towards attached growth and to provide for biological resilience in the event of spills or reactor leaks. The reactors were allowed to fluctuate with ambient temperatures. As all tanks were located above ground, the temperature variation was much greater than it would have been if the tanks were located underground.

Two identical membrane modules were used for this study. Both modules contained five 5.2 mm in diameter tubular ultrafiltration membranes (X-flow modules, Pentair) made out of polyvinylidene fluoride (PVDF) with an average pore size of 0.03 µm. Each module was 112 cm long with a total active surface area of approximately 0.093 m^2. Membrane feed was circulated through the module using a peristaltic pump (Cole-Parmer) providing a cross flow velocity (CFV) of 0.1 m/s. The concentrate passed through a gas/liquid separation chamber before returning to the second reactor. The concentrate return was located below the membrane feed pump intake, to allow large flocs and solids to settle to the bottom of the reactor rather than being constantly cycled within the filtration loop. Both modules were backwashed at 5 LMH for 10 seconds after every 45 minutes of filtration. The water used for backwashing was permeate taken from the permeate reservoir. The desired flux for this experiment was 5 LMH, which resulted in a HRT for the system of 1 day.

The reactor was housed in a metal shed located on the grounds of an elementary school (Learning Gate Community School, Lutz, FL.). Wastewater exiting the school's grinder tank was pumped directly to a 20 liter wastewater reservoir using a submersible pump. Constant mixing of the wastewater prevented settling of particulates within the reservoir. The reservoir was provided to buffer flow and strength variations of the feed. From the reservoir, wastewater was pumped into the reactor to maintain a constant level. Permeate from the system was pumped back to the school's septic tank for final disposal.

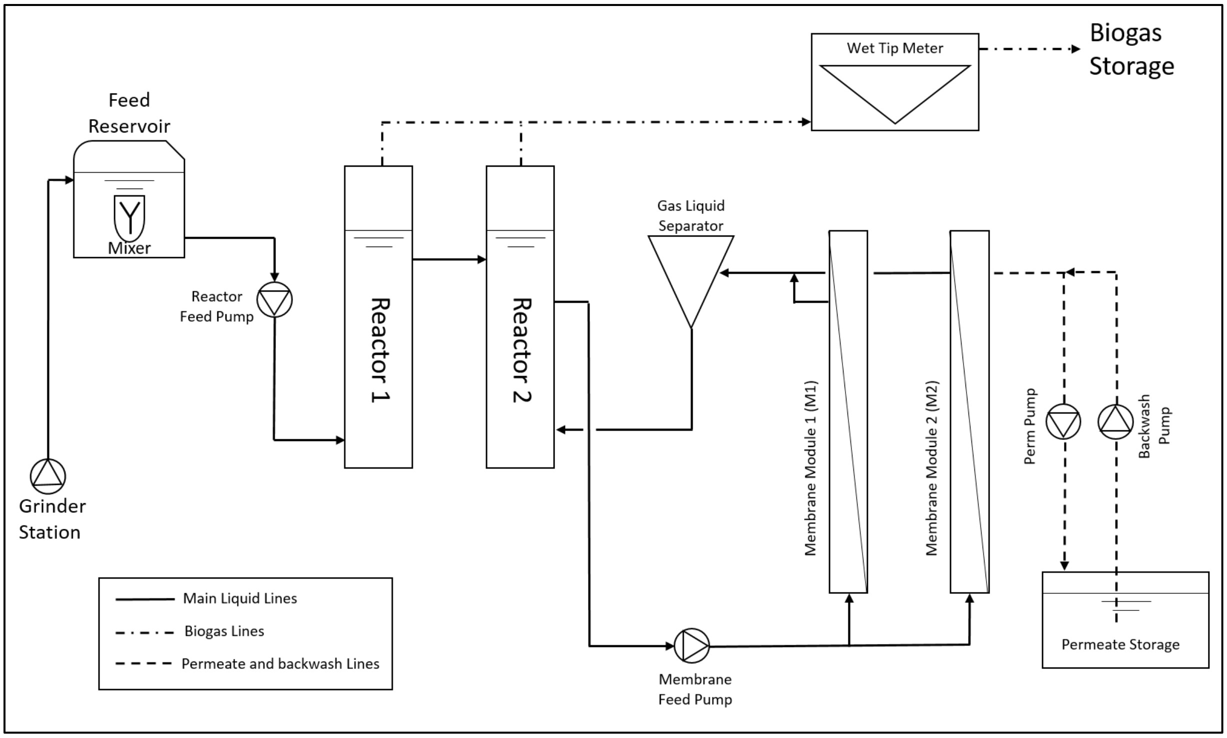

Figure 4.1: Reactor configuration.

4.2.2 Inoculation

The system was seeded with mesophilic digester sludge obtained from a local wastewater treatment plant (Howard F. Curren Advanced Wastewater Treatment Plant, Tampa, FL.). The sludge was screened with a no. 20 sieve to remove large particles, fibers, and other material that would risk clogging the membrane tubes. Both reactors were inoculated with 6 liters of sludge with a total suspended solids (TSS) concentration of 21.8 ± 0.3 g/l and a volatile suspended solids (VSS) concentration of 14.8 ± 0.3 g/l. The system was then run for 2 months allowing for process stabilization prior to testing.

4.2.3 Operational Conditions

4.2.3.1 Phase 1: High Temperature Baseline

For the baseline performance, the reactor described was operated during a Florida summer to observe its performance when subjected to relatively high ambient temperatures. During this 21 day run, the average reactor temperature was 25.6°C with a standard deviation of 3.9°C. The max reactor temperature during this run was 35.7°C and the minimum value during this run was 16.3°C. The reactor was run throughout the day and experienced a diurnal temperature fluctuation. The average spread from the day time high to the night time low was 9.3ºC. There were however a number of days where the diurnal temperature swing was well over 12ºC.

4.2.3.2 Phase 3: Lower Temperature Baseline

The second run followed an extensive chemical cleaning of the membrane, which restored the membrane permeability back to within 96% of the virgin membrane's original clean water permeability. During this 18 day period, the average reactor temperature dropped to 18.9ºC with a standard deviation of 4.4ºC. The maximum temperature during this period was 29ºC with a minimum value of 8ºC. The average spread from the day time high to the night time low decreased to an average of 7ºC during this run.

4.2.3.3 Phase 3: Artificial Heating of System

This phase followed the low temperature baseline, but the system was artificially heated to an average of 28ºC using a small space heater within the shed. This phase was done to establish whether or not membrane performance was correlated to temperature, or if it was an artifact from previous runs, including changes in biological properties. After 20 days of operation with artificial heating, the heater was removed and the temperature was allowed to fluctuate again with ambient temperatures for 7 days. During these days, the average daily temperature was 16.4ºC with a standard deviation of 4.3^{0}C. The max during this period was 25ºC and minimum temperature was 9.7ºC.

4.2.3.4 Clean Water Testing

After the artificial heating phase, both membrane modules were removed and brought to the lab for further testing. In the lab, the membrane modules were tested for permeability at three different temperatures, 10 ºC, 20 ºC, and 40ºC using tap water. The membranes were not cleaned prior to testing to see if the foulant layer on the membrane surface contributed towards the temperature sensitivity of membrane permeability. Once the membrane flux was determined for each temperature, the membrane was cleaned using a 500 ppm NaOCl solution for 30 mins. After cleaning, the membrane was tested a second time for membrane permeability using the same three temperatures. This was done to determine the effects of temperature on membrane permeability in a clean state.

4.2.4 Water Quality Testing

Samples were collected from the feed reservoir, Reactor 1, Reactor 2, and the permeate lines twice a week. The sampling point for Reactor 1 was above the sludge blanket, which means that only the supernatant of the reactor was tested. Biogas samples were pulled directly from the headspace of the reactor using Tedlar gas bags. Temperature, pressure, permeate, and biogas production were continuously monitored using data loggers (ONSET, Bourne, MA). Pressure was monitored using transducers (Cole-Parmer, Vernon Hills, IL) located on the feed, concentrate, and permeate side of each membrane module. Biogas was monitored using a wet tip meter while permeate was measured using a low-flow permeate meter.

Turbidity, TSS, VSS, pH, and alkalinity were analyzed on the liquid samples using tests described in Standard Methods (Eaton et al., 2005). COD and nutrient tests including NH_4^+, PO_4^{3-}, and total nitrogen (TN), were conducted using HACH digestion vials (HACH Company, Loveland, CO). Soluble COD (CODs) and soluble nutrient values were obtained from the supernatant of raw samples that had been centrifuged at 3,000 RPM for 20 minutes. The particulate fraction of COD (CODp) was calculated by subtracting CODs from the total COD (CODt).

4.3 Results and Discussion

4.3.1 Reactor Performance

During all three trials, the average incoming CODt in the feed was 272.3 g/L, while the average permeate CODs was 60.54 g/L leading to an average COD removal of 73%. The wastewater created at the school was very dilute in nature, which was primarily the result of low defecation rates and a high amount of dilution water. Part of the reason for such a low CODt removal rate was the low biodegradability of the incoming COD. A summary of the individual phases can be found in Table 4.1. As can be seen in a comparison between the three stages, Phase 2 had the highest average COD loading rate and also the lowest average temperature of the three runs. In all three phases the average turbidity removal was over 89%, which can be expected from membrane systems. However, an increase in turbidity was noticed in the permeate lines as time progressed. This was attributed to regrowth of microbes in the permeate line and possible precipitation of inorganics on the permeate side. As can be expected from anaerobic systems, ammonia removal was negligible during all three phases.

While this study's purpose was not exclusively on the biological performance, ensuring that the biology was not significantly compromised during the study was important. Also it was important to ensure that the influent characteristics did not vary so significantly as to skew the results of the study. Performance results for the individual phases are also included in the breakdown of each individual phase.

4.3.2 Phase 1: High Temperature Baseline

The filtration performance during Phase 1 can be found in Figure 4.2. For analysis and comparison purposes, the two modules have been labeled as M1 and M2. As shown in the figure, both modules started with low TMPs of approx. 0.1 bar. After day 3, the performance of the two modules starts to deviate, as M2's TMP begins to exhibit greater variability. M1's TMP continues to remain low until day 10, when a large increase in TMP is observed. From day 10 onward, both modules' TMP values increase and decrease with cyclic regularity, following a similar pattern as that of the daily temperature fluctuations. There seems to be two distinct stages of membrane operation, particularly in respect to temperature variability. In the first phase the membrane performance is independent of temperature fluctuations, while in the second phase the total resistance (R_T) has some temperature dependence. When we graph TMP vs temperature for these two different stages, as can be seen in Figure 4.3, this trend becomes apparent. Figure 4.3 only shows the results of M2, as the temperature dependence in M1 was not as significant during phase 1. The treatment performance of the system during this phase is shown in Figure 4.4.

Table 4.1: Summary of treatment during all 3 phases.

	Phase 1			Phase 2			Phase 3		
Parameter	In	Out	%Removal	In	Out	% Removal	In	Out	% Removal
CODt (mg/L)	160.1	35.9	74.1	291.1	91.1	66.3	210.4	56.3	68.7
CODs (mg/L)	57.2	35.9	26.0	160.8	91.1	42.0	99.8	56.3	42.3
Turbidity (NTUs)	75.4	4.3	93.6	132.3	11.9	90.8	97.1	5	89.0
NH4 (mg-N/L)	46.6	50.2	-13.4	105.7	124.6	-12.3	50.6	62.5	-23.8

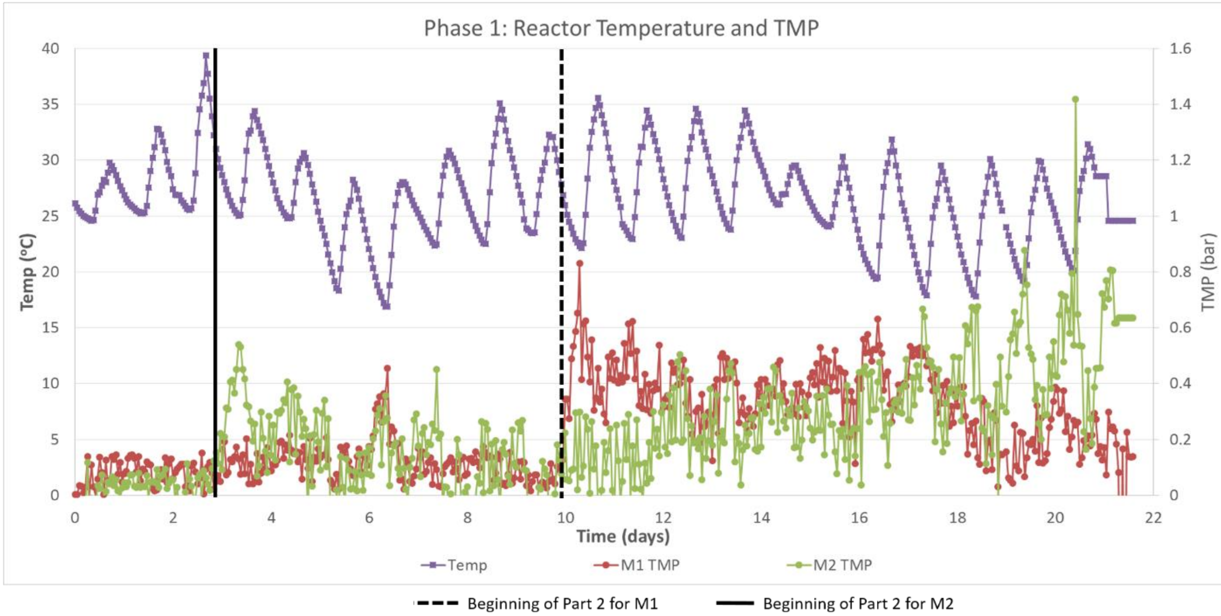

Figure 4.2: Membrane performance during Phase 1. Graph shows the TMP of both modules as they relate to reactor temperature. The solid vertical line indicates when M2 module started to exhibit a temperature dependent TMP variations. The second vertical dashed line indicates when M1 started to exhibit temperature dependent variations.

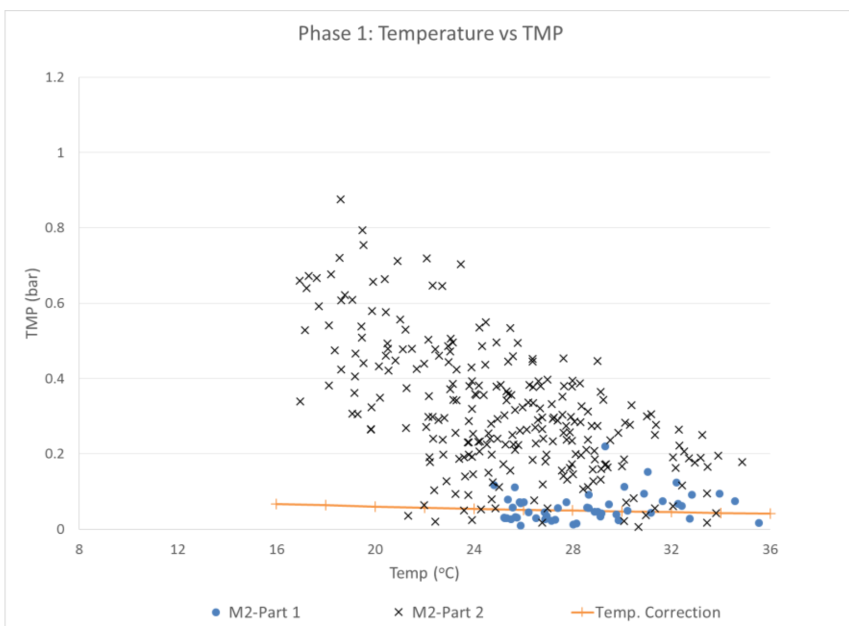

Figure 4.3: TMP vs Temperature for M2 during Phase 1. Part one includes days 1-3 and Part 2 includes days 3-20. A Temperature correction factor, described in equation 4.1, is also shown to represent the amount change in TMP that can be accounted for by changes in permeate viscosity.

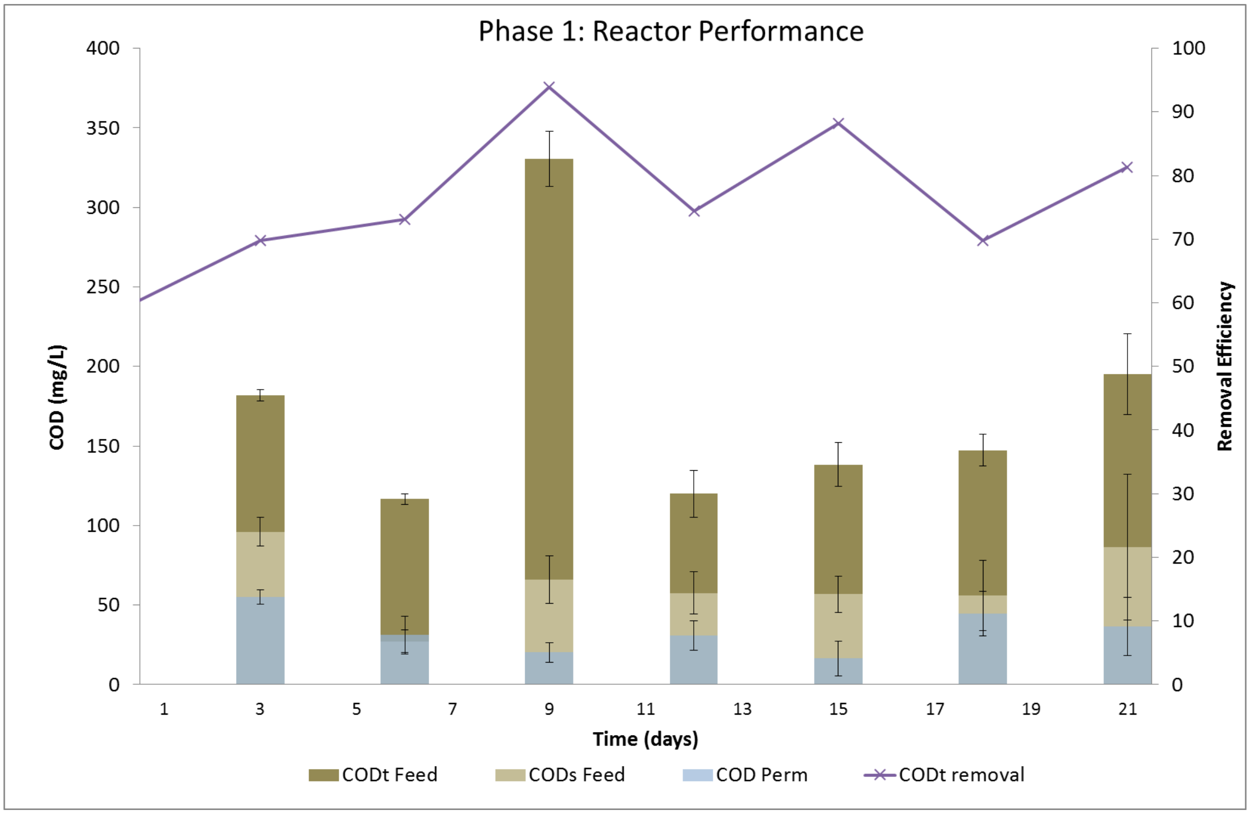

Figure 4.4: Treatment performance of AnMBR during Phase 1. Bar categories are overlapping each other.

4.3.3 Phase 2: Lower Ambient Temperatures

A summary of the membrane performance during Phase 2 can be found in Figure 4.5. Phase 2 started similar to Phase 1, with low TMP values for both modules up until day 8. At that point, the membrane flux was increased momentarily to 10 LMH. By day 10, the flux was reduced to the normal operation flux of 5 LMH. Following the increase in flux, both module's TMP exhibited a strong relationship with reactor temperature, with M1 exhibiting the strongest relationship. As was seen in Phase 1, the operation seems to follow two distinct stages, one before and one after slight membrane fouling. These two stages are even more discernable when plotting membrane TMP vs temperature as seen in Figure 4.6.

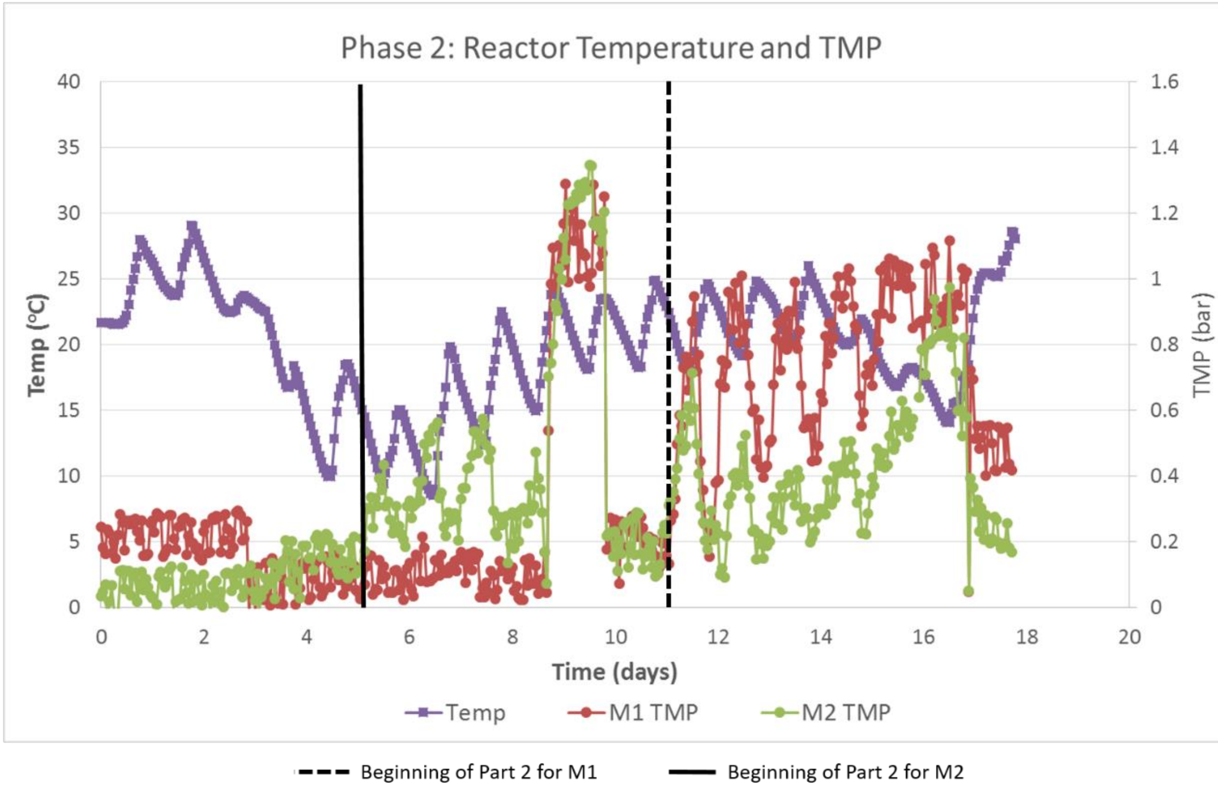

Figure 4.5: Membrane performance and temperature fluctuations during Phase 2. The vertical lines represent the points at which the membrane modules started to exhibit temperature dependence.

In Phase 2, the temperature range for both stages was much wider, allowing us to observe the membrane performance from 8ºC to 29ºC. During the first stage, the membrane's TMP seems to be completely independent of temperature changes. In the second stage of membrane performance, the correlation between temperature and TMP is quite clear, showing a negative relationship. At lower temperatures, the TMP can increase by up to 5 times, from a TMP of 0.2 bars at 20ºC up to 1 bar at 14ºC. Despite the poor membrane performance, the reactor displayed adequate COD removal during this phase. COD removal performance is shown in Figure 4.7.

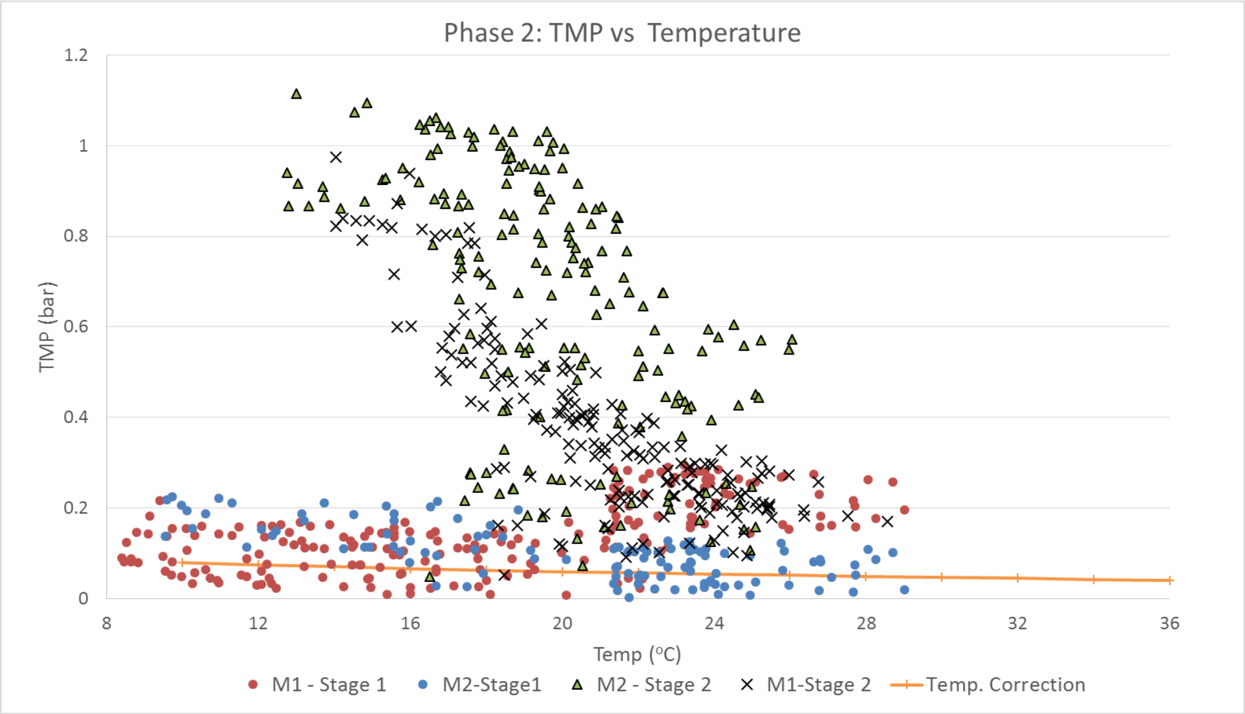

Figure 4.6: TMP vs Temperature plots for both membranes during Phase 2. The temperature correction line reflects changes in TMP that can be accounted for by changes in permeate viscosity, as described in equation 4.1.

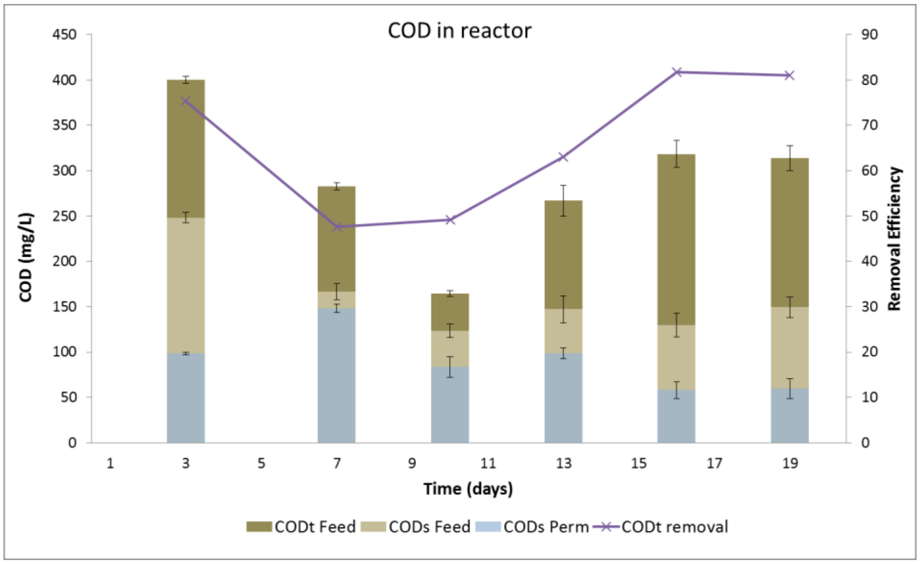

Figure 4.7: Reactor performance during Phase 2. Categories bars are overlapping each other.

4.3.4 Phase 3: Artificial System Heating

Phase 3 was conducted to ensure that the variability in the TMP was not a result of some other diurnal fluctuation, either from changes in the influent characteristics or biological changes that were independent of temperature. The membrane performance can be seen in Figure 4.8. The high variability in TMP that was observed in the first two runs was absent from the first part of this run, when the running temperature was maintained constant. During this run, the TMP gradually rises in both membranes after day 10. This type of membrane fouling is more common and is the expected fouling behavior exhibited in MBRs. Once the artificial heating was removed, the TMP immediately spiked, indicating a high temperature dependence of TMP. However, when the TMP is plotted against temperature during the last week of operation (see Figure 4.9), the temperature dependence of TMP is not as strong as it was during Phase 2.

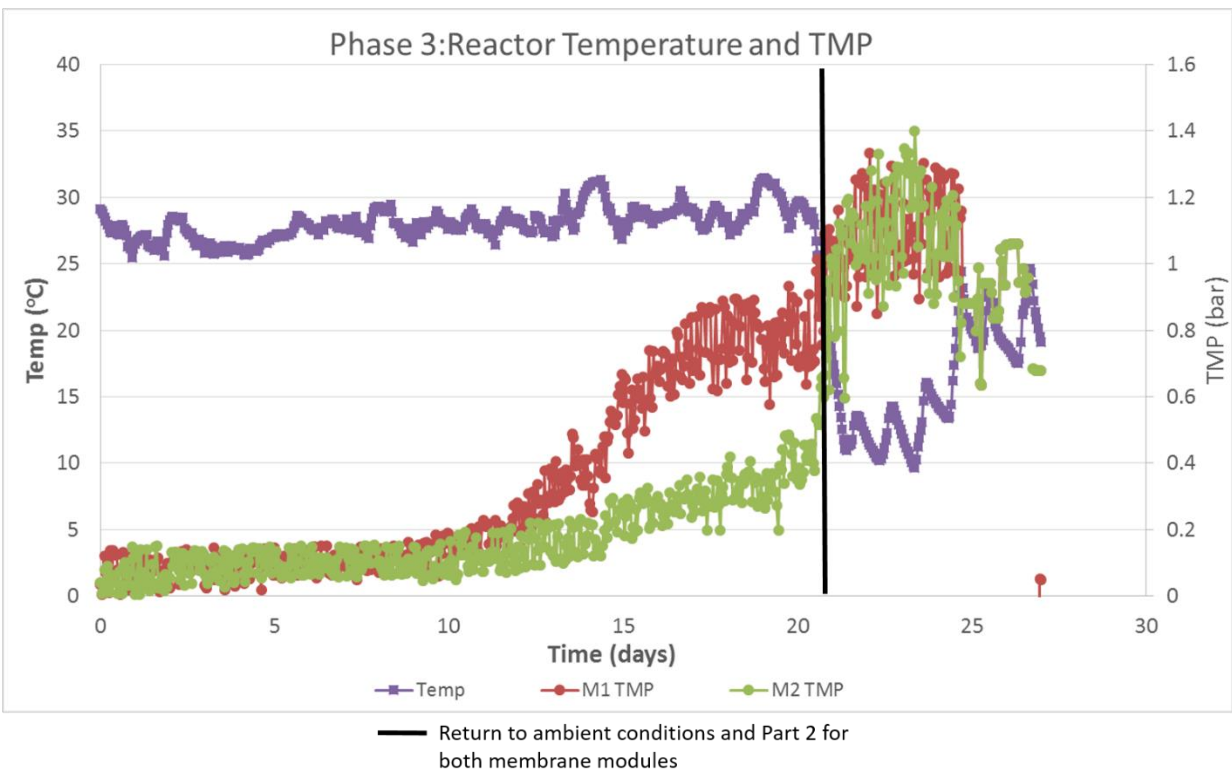

Figure 4.8: Membrane performance and reactor temperature during Phase 3. Vertical bar represents when the artificial heating was removed from the system and indicates the date at which Part 2 temperature dependence was calculated.

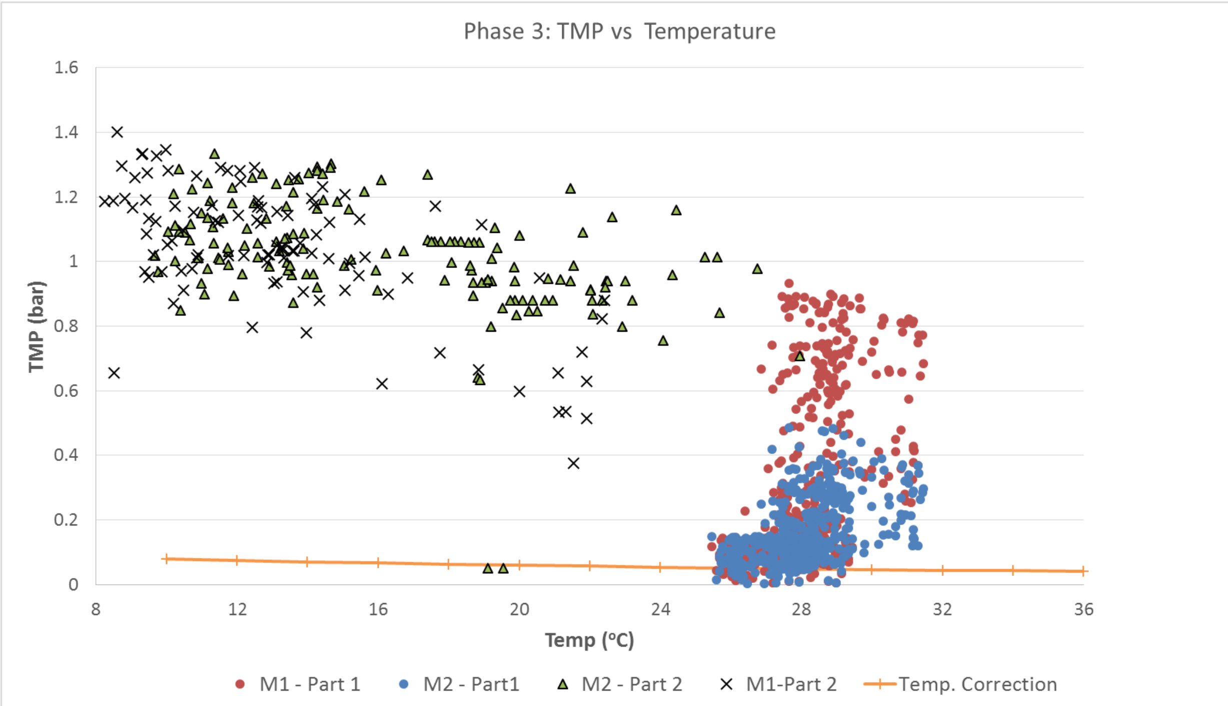

Figure 4.9: TMP vs temperature during Phase 3. The temperature correction factor accounts for TMP changes resulting from changes in permeate viscosity.

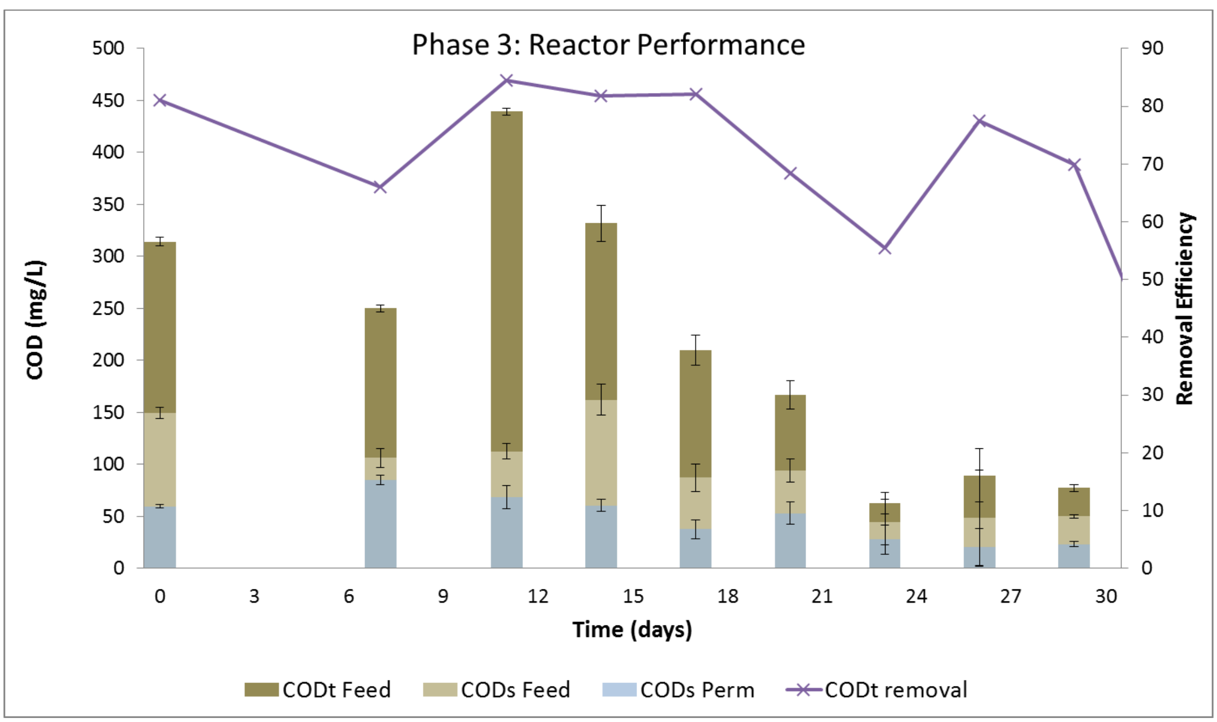

Figure 4.10: Reactor performance during Phase 3 of study. Bar categories are overlapping.

4.3.5 Fouled and Clean Membrane Water Testing

As a final test, the fouled membranes from Phase 3 were tested for clean water permeability. This test was conducted to understand the influence that the foulant layers, still present on the membrane surface (visible in Figure 4.10), would have on the total membrane resistance. Total membrane resistance is often calculated using a resistance in series model described in Equation 4.3 (USEPA, 2005):

$$R_t = R_m + R_f \tag{4.3}$$

where R_T is the total filtration resistance (m^{-1}), R_m is the resistance of the membrane material (m^{-1}), and R_f is the resistance of the foulant layer (m^{-1}). The nature and temperature dependence of the R_T is important as it directly impacts TMP through Equation 4.4 where:

$$J_T = \frac{TMP_T}{R_{tT} \times \mu_T} \tag{4.4}$$

where TMP_T is the transmembrane pressure at temperature T (bar), J_T is the membrane flux at temperature T (LMH), R_{tT} is the total filtration resistance (m^{-1}), and μ_T is the permeate viscosity at temperature T (cp).

When tap water of three temperatures were passed through the fouled membrane, there was a clear correlation between membrane permeability and temperature as can be seen in Figure 4.12.When the membrane modules were cleaned and retested using the same water temperatures, this correlation was no longer present. The test performed with the clean membrane modules indicates that R_m does not significantly change with changes with the temperatures observed in this study. This was further collaborated by the minor temperature dependence of the TMP observed with clean membranes in the previous three phases. However, the temperature dependent changes in flux that are observed this test suggest that the R_f is what is contributing the TMP fluctuations observed in the previous phases. However, with this simplified test it is impossible to distinguish between cake layer, pore clogging, or any other fouling mechanism that contribute towards R_f. All that is known is that the total fouling resistant R_f is affected by temperature and follows the same correlation found throughout the initial three phases.

Figure 4.11: Feed side view of M2 after it was removed from the testing system. The foulant layer, visible as a brown stain can be seen running the length of the membrane module.

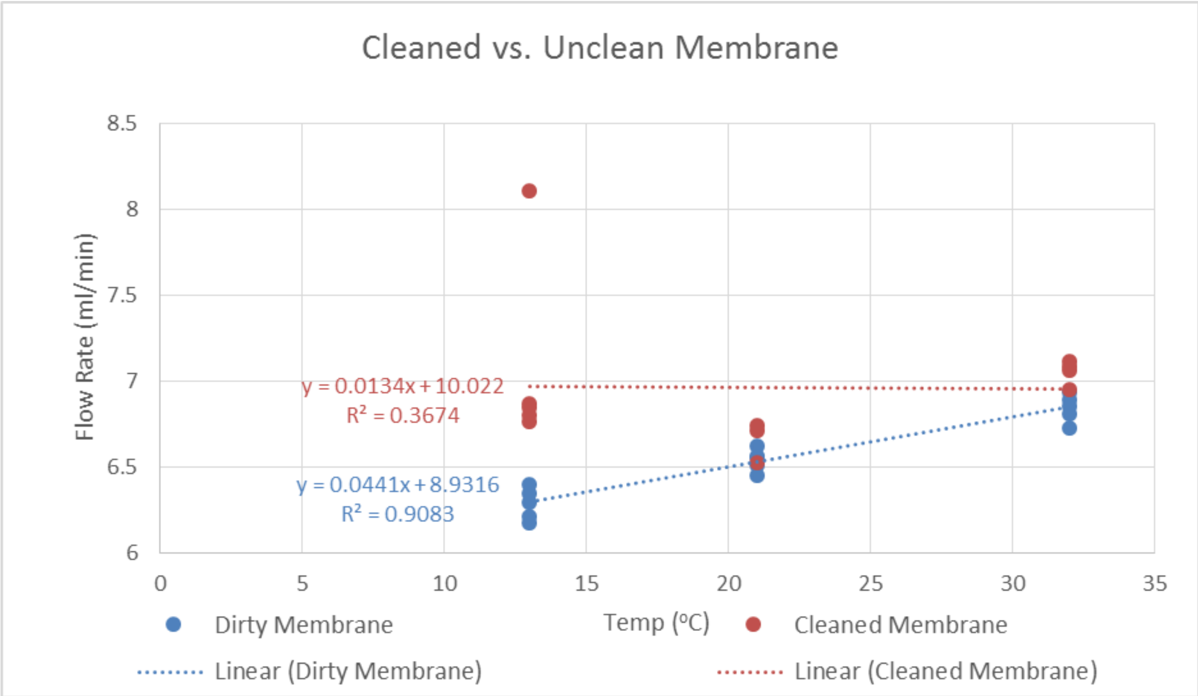

Figure 4.12: Membrane permeability, clean vs fouled membrane.

4.3.6 Temperature Correlation

From the following three phases it is apparent that the there is a correlation between TMP and temperature in slightly fouled membranes. What is clear is that virgin and recently cleaned membranes are not significantly affected by changes in the operating temperatures found in this study. The membrane material selected, PVDF, is known to be stable when operated at temperatures below its glass transition temperature (Gao et al., 2011). As such, significant changes in membrane porosity and/or density should not be expected within the temperature range found in this study. During the first stage of membrane operation, the temperature correction factor (Equation 4.1) adequately describes the relationship between TMP and operating temperature.

In the first two phases, once the TMP started to increase (the result of membrane fouling), the total resistance has a stronger temperature correlation. This becomes even more apparent when the total resistance (R_t) is plotted according to temperature which can be seen in Figure 4.13. Using the data from Phase 2, a strong negative correlation between operating temperature and R_t can be found. Shifting the reactor temperature from 25ºC to 15ºC could result in a 2.4 fold increase in TMP. This correlation cannot be explained by existing temperature correction factors, which primarily focus on water viscosity as the reason for changes in TMP. When using temperature correction factors, viscosity can only account for a 31% increase in TMP for the same temperature range. Another observation is that the increase in TMP was highly reversible without the use of external or operational changes (i.e. backwashing, gas sparging etc.). The final test suggests that the combined effect of all biofouling mechanisms, including cake layer, pore blocking, and clogging had variable and reversible fouling resistance which was affected by temperature.

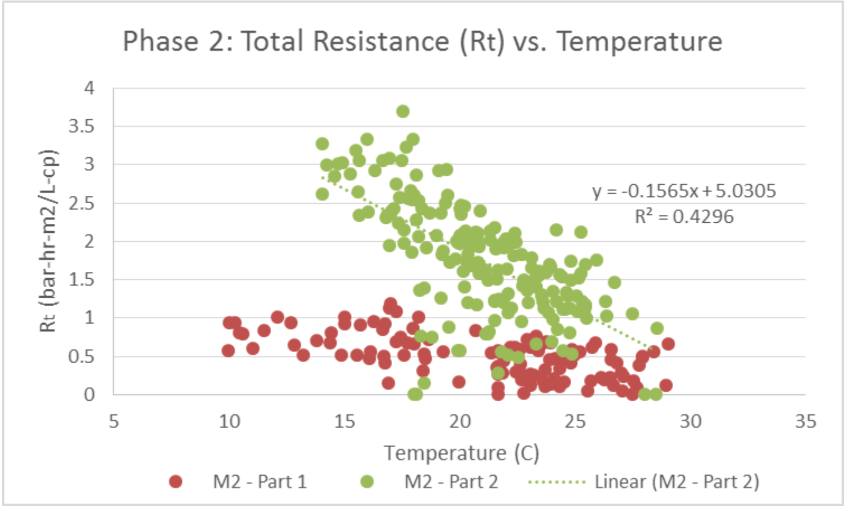

Figure 4.13: Total resistance vs operating temperature in Phase 2 for membrane module 2. R_t was calculated using equation 4.4.

One possible explanation for this phenomena would be the large buildup and release of soluble microbial products (SMPs), such as polysaccharides and proteins which microbes generate when stressed (Barker & Stuckey, 1999). Drews et al. observed a large buildup of SMPs in aerobic MBRs when temperatures were artificially lowered (2007). This same study noted that the SMP levels led to higher fouling rates which were highly reversible when the temperatures were subsequently increased. SMPs are known to play a large role in membrane fouling and could potentially explain a portion of why the membrane fouling seems to be temperature dependent (Barker & Stuckey, 1999). However, this mechanism would not have played as much of a role in the final test conducted in our study. By testing the fouled membrane module after it had been separated from the reactor, a sudden release of SMP could not have affected the membrane's performance. However, a release of SMPs can contribute towards more complex fouling mechanisms including a rapid growth of a cake or gel layer on the membrane surface.

Van den Brink et al., proposed five possible mechanisms that could explain similar results in aerobic MBRs (van den Brink et al., 2011).

These include:

1. Increased mixed liquor viscosity leading to reduced sear stress from aeration
2. More severe deflocculation, leading to greater levels of extracellular polymeric substances (EPS)

3. Lower particle back-transport velocity
4. Reduced biodegradation of COD
5. Changes in cake layer thickness and/or porosity

The first mechanism does not apply well to this experiment, as this study did not rely on gas sparging for fouling control. However, reduced viscosity would lead to a decrease in pump efficiency resulting a decrease in the effective CFV seen in the membrane module. A lower CFV would allow for a more rapid foulant accumulation on the membrane surface. As for the second mechanism, temperature is known to affect the morphological properties of anaerobic flocs, however, studies show a negative correlation between floc size and temperature (Gao et al., 2011; Jarvis et al., 2005). Thus, one would expect greater floc sizes at colder temperatures which would result in decreased fouling, which would be the opposite trend seen during these studies. The fourth mechanism would have similar results to the rapid shifts in SMP production discussed earlier. While this might influence the temperature dependence observed in the study, the clean water test of the fouled membrane would not have been directly influenced by this mechanism.

Changes in back-transport velocity would lead to greater fouling at lower temperatures. If changes in back-transport velocity led to a compact cake layer at the membrane surface, the reversibility of that resistance is likely to be low. If, however, that cake layer, composed of SMP, cells, and macromolecules, has a porosity and thickness that changes with temperature, then the changes in TMP would be reversible when the temperature increased. Thus, the fifth mechanism described seems to be the most appropriate to explain what is observed in this study. However, as was observed in Phase 3, when the membrane was severely fouled, changes in temperature did not affect R_T as much. This could be a result of permanent compaction of the cake layer. Compaction at higher TMPs could have prevented the cake layer from reacting to temperatures as it previously did when it was only slightly fouled.

4.3.7 Operational Considerations

Knowing that membrane systems, even ones that are only slightly fouled, can experience large TMP increases during low temperatures will allow operators to design maintenance and operational protocols aimed at minimizing energy use during those events. One maintenance protocol that would benefit performance, would be to implement frequent chemical cleaning and more aggressive anti-fouling protocols prior to cold events or seasons. For decentralized MBRs, a specific overdesign of the membrane system will allow for maximizing the operation during times when temperatures are highest. Decentralization of wastewater treatment can also benefit by being closer to the point of discharge, where temperatures are highest during cold seasons. Strategic planning and operations based around temperature fluctuations can help to prevent a failure of the membrane system.

4.4 Conclusions

Decentralized wastewater treatment systems experience large fluctuations in wastewater temperatures as they lack extensive collection systems to buffer or equalize incoming flows. Daily and seasonal temperature variations can have negative impacts on MBR performance beyond its impact on biological treatment. This study looked at the connection between reactor operating temperature and transmembrane pressure. Membrane performance followed two distinct stages, one exhibiting no correlation to temperature, while the second was strongly correlated to temperature changes. The first stage was seen with virgin and recently cleaned membranes, while the second stage was observed on slightly fouled membranes. However, this correlation was not as strong with a severely fouled membranes. The membrane TMP was seen to increase by 2.4 times when the operating temperature decreased from 25ºC to 15ºC. Once a fouled membrane was removed from the reactor skid and tested with clean water, this temperature relationship was still observed. Temperature dependent changes in the foulant layer porosity and density is likely the mechanism responsible for the phenomena observed in this experiment. Changes in reactor operation, such as more frequent cleaning and more aggressive fouling control measures, could be used during seasons and periods of greater temperature fluctuations to minimize the energy used by AnMBR for domestic wastewater treatment.

4.5 References

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Chapter 5: Feasibility of Anaerobic Membrane Bioreactors (AnMBR) for Onsite Sanitation and Resource Recovery in Urban Slums.[3]

5.1 Introduction

Slum dwellers are some of the most vulnerable and impoverished citizens of urban centers 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 like 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 need 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 (8-9 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

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[3] The contents of this chapter are published in: Bair, R. A., Ozcan, O. O., Calabria, J. L., Dick, G. H., & Yeh, D. H. (2015). Feasibility of anaerobic membrane bioreactors (AnMBR) for onsite sanitation and resource recovery (nutrients, energy and water) in urban slums. Water Science and Technology, 72(9), 1543-1551. The final Publication is available at Iwaponline at http://wst.iwaponline.com/content/73/6/1492.

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 achieving this desired goal. Defined simply, an 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 (Fenner et al., 2007; Liao et al., 2006).

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.

5.2 Materials 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 was acquired from Eram Scientific Solutions (ESS), a company based out of Kerala, India that 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 Thiruvanathapuram, Kerala. From these headquarters, maintenance crews are dispatched in the event of a user's complaint or a system malfunction. The sensor data also activates automated cleaning procedures that help to reduce the need for human labor. Urination and defecations events were distinguished by ESS according to the duration of each individual event. Events lasting more than five minutes were assumed to be defecation events and anything under five minutes was assumed to be an 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. The assumptions and characteristics of the wastewater can be found in Table 5.1.

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 liters/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.

Table 5.1: Feed characteristics for the AnMBR. References [1] Jonsson et al. (2005), [2] Nishimuta (2006), [3] Heaton et al. (1993).

Feed Assumptions and Characteristics			
Parameter	Value	Unit	Ref
% Users Defecating	40.0%	Of total events	
% Users Urinating	95.0%	Of total events	
Moisture content of faeces	73.0%		[2]
Avg. defecation water volume	0.11	L/ca/d	[1]
Avg. urination water volume	1.4	L/ca/d	[1]
Total COD of urination	8.5	g/ca/d	[1]
Soluble & biodegradable COD of urination	7.23	g/ca/d	[1]
Total nitrogen of urination	11	g/ca/d	[1]
Total COD of defecation	37.3	g/ca/d	[1]
Total Phosphorus from urination	0.9	g/ca/d	[1]
Soluble & biodegradable COD of defecation	5.2	g/ca/d	[1]
Total nitrogen of defecation	1.5	g/ca/d	[1]
Total Phosphorus from defecation	0.5	g/ca/d	[1]
Defecation event wastage fraction	100%	of daily waste	[3]
Urination event wastage fraction	25%	of daily waste	
Flush volume for urination	1	L/event	
Flush volume for defecation	4	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	

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 5.2.

Table 5.2: 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	1714 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

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 Thiruvanathapuram, Kerala were used to estimate the surface area required to heat all incoming feed to 60^{o}C for a minimum of 20 minutes. Average winter temperatures for Kerala were used to 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, 2012). A multiple barrier approach is used to enable multi-log pathogen destruction to ensure maximum microbial safety for water reuse: 1) thermal pretreament 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) 5) biosolids and trash removal via onsite incineration . While this level of processing many 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 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 isolation values found in Kerala, India. Biogas produced by the reactor was assumed to be stored within a 1 m3 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 solar drying and onsite incineration. Many of the assumptions used to calculate the energy values can be found in Table 5.3.

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 size 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 5.4.

Table 5.3: Energy assumptions and calculations used to determine the energy balance of the combined system. References: [4] Rittman & McCarty (2012), [5] Lettinga (1995), [6] Hegde & Ramachandra (2012), and [7] Goswami et al. (2000).

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	-	[4]
% CH4 in Biogas	65%	-	[5]
CH4 Yield	0.350	L CH4/g COD	[4]
Heating Value of CH4	52.8	kJ/g	
Biogas Mean Molecular Weight	25.8	g/mol	
Daylight Hours (Winter)	4	h	[6]
Daylight Hours (Avg.)	6.5	h	[6]
Solar PV Yield	193.17	W/m2	[7]
Solar PV Performance Ratio	0.7	-	[7]
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/m2/d	[6]
Solar Insolation (Winter)	4.8	kWh/m2/d	[6]
Solar Thermal Efficiency	65%	-	[7]

Table 5.4: Food waste characteristics and assumptions. Reference: Zhang et al. (2007)

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

5.3 Results and Discussion

The mass, energy and water balance shows favorable 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 one can be found in Figure 5.1. The majority of the energy required for the combined system comes from preheating the incoming feed to 60ºC. During 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 requirements 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.

The nutrient and element balance, featured in Figure 5.2, 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. Odor in the recycled water is another potential concern. Chemical means of removal, 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.

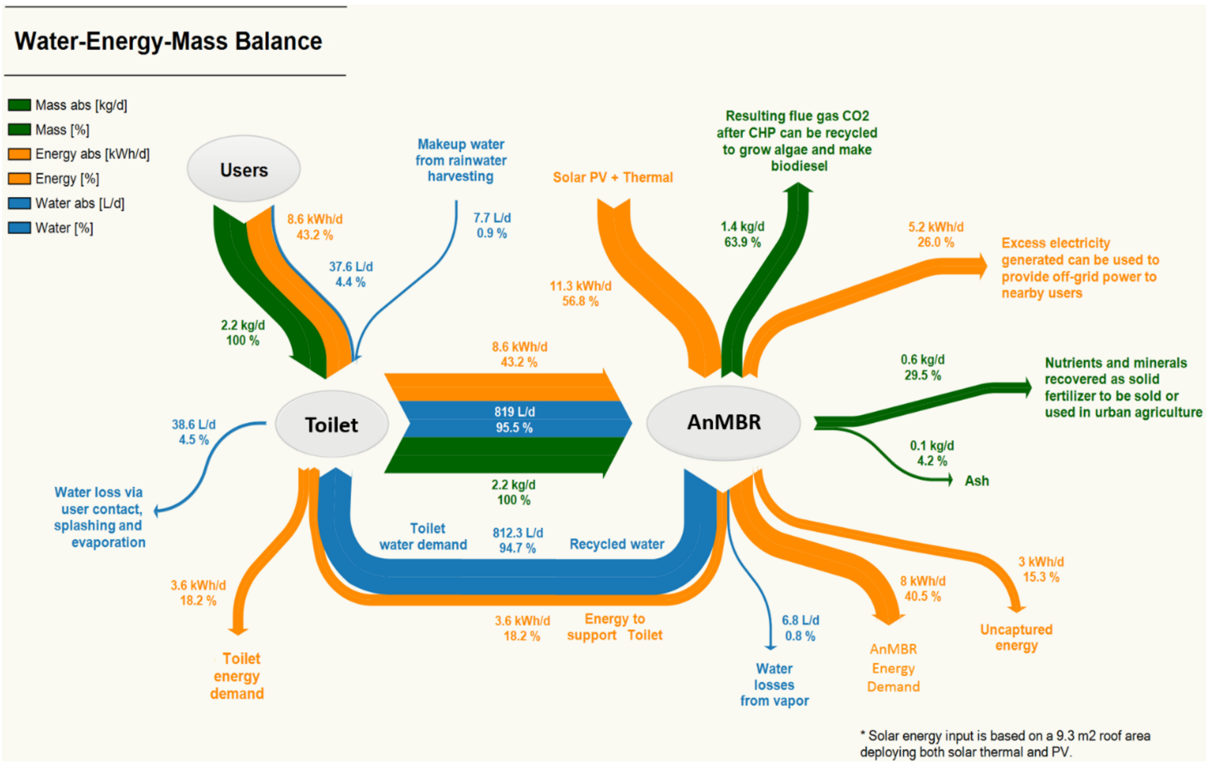

Figure 5.1: Water-Energy-Mass Balance summary for the combined eToilet and AnMBR system.

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 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 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 5.3.

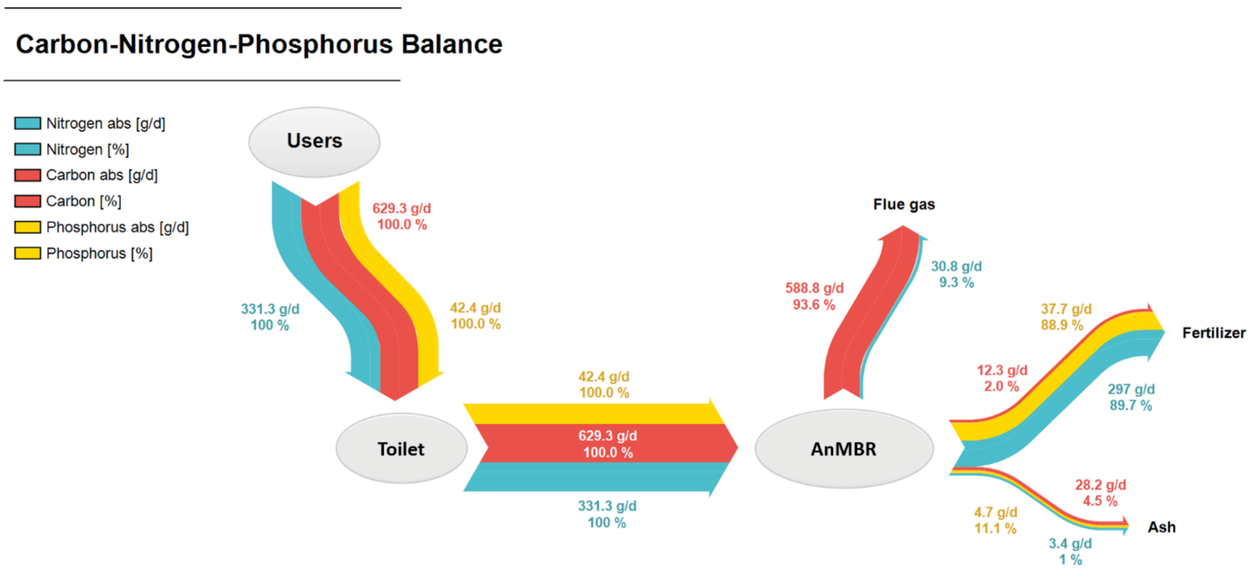

Figure 5.2: Nutrient and element analysis for combined electronic toilet and AnMBR system. The diagram shows nutrient flows and recycling between the system components.

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 personal for storing and maintaining the nutrient recovery subsystems. A summary of the Carbon-Nitrogen-Phosphorus balance for scenario 2 can be found in Figure 5.4.

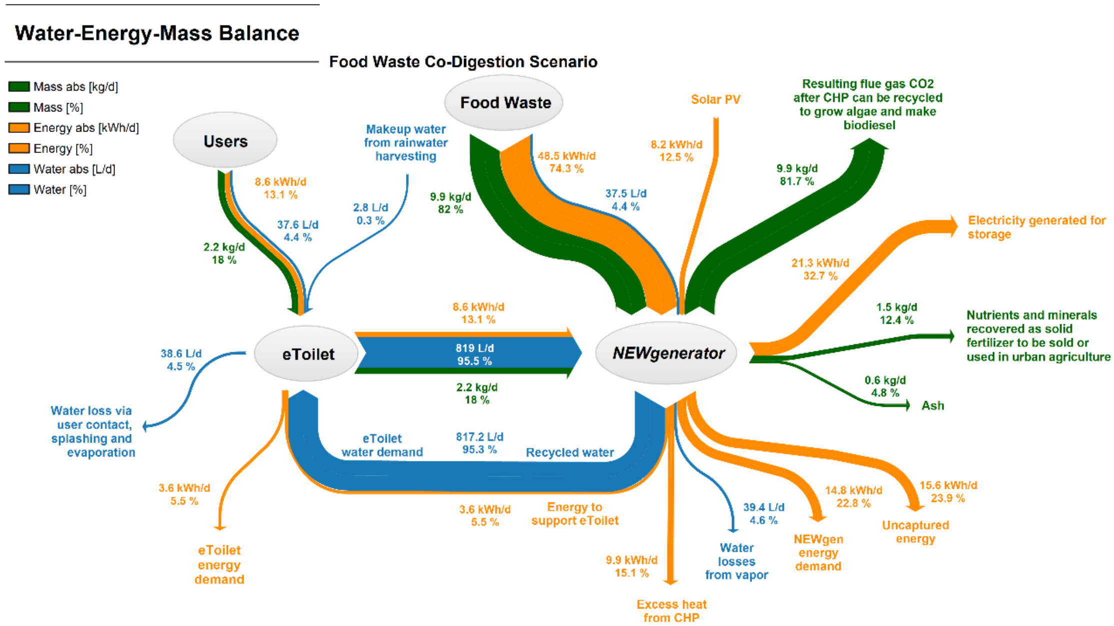

Figure 5.3: Water-Energy-Mass Balance summary for the combined eToilet and AnMBR system under scenario 2 which includes food waste addition.

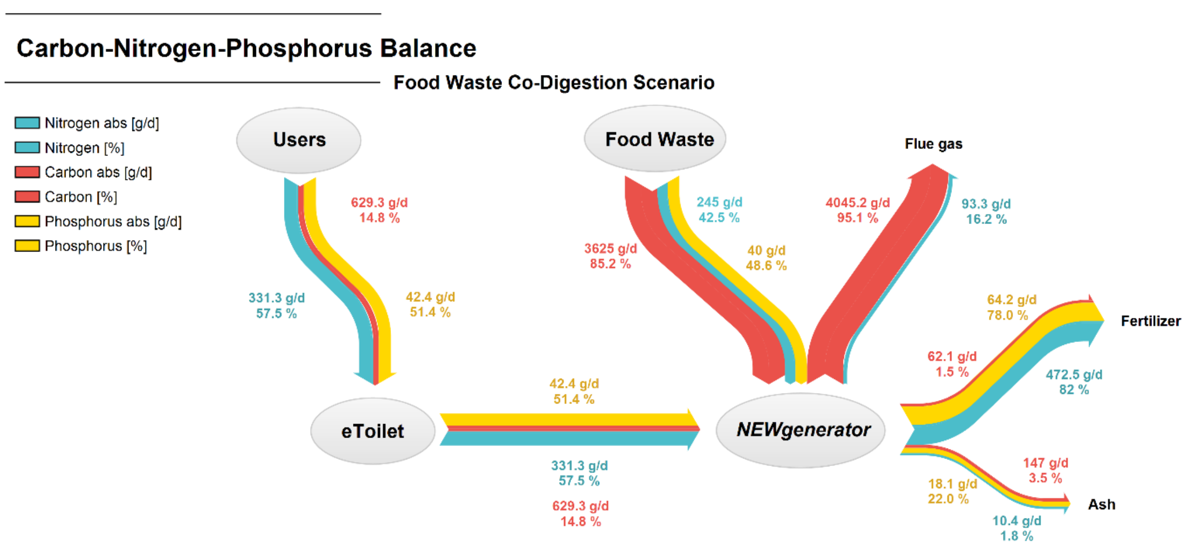

Figure 5.4: Nutrient and element analysis for combined electronic toilet and AnMBR system with the addition of food waste.

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.

5.4 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, or plant uptake will be required to prevent ammonia accumulation within the AnMBR system. Future studies should aim at lab 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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Chapter 6: Design and Operation of a TRL7 Off-grid Anaerobic Membrane Bioreactor for Onsite Resource Recovery

6.1 Introduction

Despite the potential and interest in anaerobic membrane bioreactor (AnMBR) technology, most investigations into the subject are limited to lab scale studies (Skouteris et al., 2012). Only a handful of papers have investigated the use of AnMBRs at the pilot scale, and even fewer have used domestic wastewater (see Table 6.1 for a summary of relevant pilot scale AnMBRs). One common trait amongst the pilot studies that have been conducted is a consistent and reliably high chemical oxygen demand (COD) removal. Membrane filtration guarantees a minimum quality of the permeate exiting the reactor, which makes the overall treatment performance more resilient to shocks and system disturbances. This benefit is particularly relevant and useful in decentralized wastewater treatment where a high degree of system reliability is required.

Despite validation of these beneficial traits at the pilot scale, no system to date has been directly applied in a decentralized setting for complete water recycling. Nor is there sufficient information regarding the energy consumption of AnMBRs at the pilot scale. The purpose of this study was to validate the conclusions presented in Bair et al., primarily that an AnMBR based treatment system can be implemented in a high density setting to achieve complete water recycling for sanitation purposes (2015). This study will also investigate the energy requirements of a completely off-grid decentralized system.

Table 6.1: Pilot scale AnMBRs that have been tested. References: [1] Shin et al. (2014); [2] Giménez et al. (2011); [3] Calderón et al. (2011); [4]Gouveia et al. (2015); [5] Dereli et al. (2012); [6] He et al. (2005). References 5 & 6 were performed using industrial strength wastewaters.

	Wastewater	**System Details**				**Membrane Details**			**System Performance**	
Ref.	Strength (mg-COD/l)	Reactor Size (m^3)	HRT (h)	Operating Temp.	React. Conf.	Material	SA (m^2)	Configuration	Avg. COD Removal %	Energy Use (kWh/m^3)
[1]	198 -362	1.76	4.6-6.8	Ambient	SAF-MBR	PVDF	40	Submerged Hollow Fiber	81	0.23
[2]	445	1.3	6 - 20	Mesophilic	--	--	60	Submerged Hollow Fiber	87	--
[3]	425	0.849	6	--	UASB	PVDF	5.02	Ext. Tubular	71	--
[4]	892	0.160	7	18°C	UASB	--	0.93	Tubular	87	--
[5]	98,000	12	408	Mesophilic	CSTR-Batch	PVDF	18	Ext. Submerged Flat sheet	98	--
[6]	20,000	0.4	60	Mesophilic	--	PES	0.3	Ext. Flat sheet	80-90	--

6.2 Materials and Methods

6.2.1 Treatment System

The AnMBR in this study was designed after the theoretical reactor presented in Bair et al., (2015). As the system was designed and constructed prior to site selection, the daily user rates, wastewater strength, and volume had to be estimated according to the average daily usage figures provided by Eram Scientific Solutions (ESS). However, it was known that those figures are highly site specific and could vary significantly depending on the final location. The uncertainty of such important parameters led to an intentional overdesign of critical components and subsystems leading to deviations between the design in Bair et al., and the system constructed for this study (2015). Using an average of 100 uses per day for two toilets, it was predicted that the system would need to treat 628 liters of wastewater per day with a strength of 2.7 g-COD/L.

To treat this high-strength and particulate laden wastewater, an anaerobic baffled reactor (ABR) was selected. The ABR was a 1,200 liter polypropylene tank (manufactured by SW Plastics, Clearwater, FL) with a liquid volume of 1,000 liters. The reactor contained 3 equal volume chambers, each connected to the following chamber by three 50 mm PVC pipes. As typical for ABRs, the maximum upflow velocity expected within the first two baffles was 0.08 m/s. The system was designed to achieve a hydraulic retention time (HRT) of 1.6 days while having an organic loading rate (OLR) under 1.7 g-COD/L/day. The first two chambers contained a 50 mm thick polypropylene porous mat which provided additional surface area for attached growth. The last chamber served as the intake for the membrane feed pump, which took contents from the middle of the chamber and pumped them towards the membrane module. The external membrane module, which consisted of 5.2 mm polyvinylidene fluoride (PVDF) tubular membranes, had a total surface area of 15 m^2. The average pore size of the membranes was 0.030 µm. The module was provided with a cross-flow velocity (CFV) of 0.2 m/s and was operated at 5 LMH for the duration of the study. The length of the membrane cycle was determined by the volume of the chlorinator tank (discussed in the following section). On average, the membrane run time was 15-30 minutes and was followed by a 10 second backwash at 120 LMH. Backwash was then followed by a relaxation step where the membrane feed pump and permeate pump remained off during chlorination. This relaxation step lasted 3-35 minutes, depending on the strength and volume of the permeate being chlorinated. Once all product water tanks were filled, the entire filtration system would go on standby allowing for even longer relaxation of the membrane module. An average daily relaxation of 8-10 hours was expected during full operation. A schematic of the reactor and membrane system can be found in Figure 6.1.

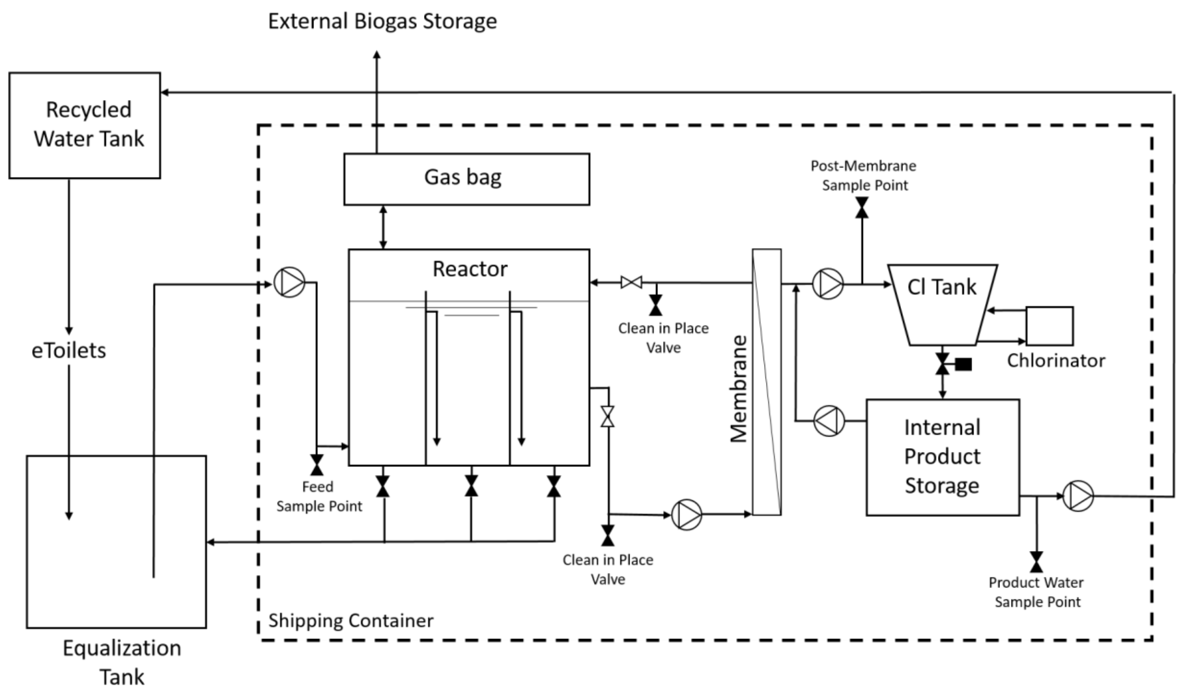

Figure 6.1: Simplified schematic of reactor and membrane system used in this study. This schematic does not show electrical or sensor subsystems.

6.2.2 Post Treatment System

After exiting the reactor, the permeate contained varying degrees of soluble COD (CODs), nutrients, and substances that contribute towards odor and color. Prior to reuse, these materials would have to be removed. An electrochlorination system (Waterstep, Louisville, KY) was selected as a polishing step to oxidize the permeate to an oxidation reduction potential (ORP) value of 700 millivolts (mv). The selection of 700 mv was based on achieving breakpoint chlorination, at which point all chlorine demand is depleted (Devkota et al., 2000). The electrochlorination system achieved breakpoint chlorination by adding Cl_2 gas to the Chlorination (Cl) tank. In addition to improving the quality of the final product water, chlorination served as a secondary and robust barrier to pathogen destruction. Electrochlorination was selected over traditional methods of chlorine dosing, as the only consumable required for this polishing step was salt.

As an additional option, permeate exiting the reactor could be passed through a hydroponics system containing zeolite and granular activated carbon (GAC) for additional nitrogen and CODs removal via adsorption (Lind et al., 2000). The hydroponics system consisted of 6 rows of 76 mm PVC pipes, each of which was 1.67m long. The grow pipes were connected in series and each contained 500 g of zeolite and 500 g of GAC. Locally sourced ornamental plants were added to the grow tubes after rinsing the soil from their root systems. The hydroponics system served as a polishing step to be used prior to chlorination in order to reduce the chlorination demand. As chlorination demand was directly tied to energy demand, this would reduce the total energy required by the system. This system required a manual bypass and was only periodically utilized within this study.

6.2.3 Housing

The entire system was contained within a rugged metal shipping container (CMCI, Dallastown, PA). This particular container was a quarter of the size of a standard 40 foot ISO shipping container. The exact foot print of the unit was 1.457m by 2.082m by 2.438m. This small footprint and the standardized attachment points of the shipping container allowed for greater ease in shipping and installation of the unit in locations with little room to spare. In addition to the small foot print, the container was made out of thick steel, making vandalism and theft of the contents difficult.

6.2.4 Biogas System

Biogas from the headspace of the reactor was allowed to equalize within a 284 liter polyester gas bag (Husky, Bartlesville, OK) mounted to the ceiling of the shipping container. This bag prevented pressurization and/or vacuum formation in the reactor headspace caused by changes in fluid level. Once filled, the biogas bag vented its contents to an external floating dome which served as the final biogas storage. The floating dome was located near the school's kitchen and could be used for cooking.

6.2.5 Energy System

The pumps, controllers, and electrochlorinator all required electrical energy to be produced and stored within the unit. Once the treatment system was designed and all electrical components were selected, an energy demand inventory was made. For this inventory, a worst case scenario was assumed and a total membrane flux of 2.5 LMH was used. The low flux was used in order to calculate the longest possible membrane run time. As described in Bair et al., a combined biogas generator and photovoltaic system was envisioned for energy production. However, once the additional maintenance, capital costs, and uncertainty related to the energy content of the waste material were considered, a single-source photovoltaics system was used. Average daily solar insolation values for the project site, Trivandum, Kerala, India were collected from Hedge & Ramachandra (2012). A total of 2.3 days of energy independence, and a maximum daily depth of discharge of 50% was used for battery bank sizing.

The final photovoltaics system consisted of a 1120 watt array at a nominal 24 volts, feeding into a 60 amp charge controller (MorningStar, Newtown, PA), and into a 14.76 kWh battery bank. The panels were mounted 152 mm from the top of the shipping container to allow for air circulation and cooling. The battery bank consisted of six, 12 volt deep-cycle lead acid batteries with 205 amp hours each (Trojan, Santa Fe Springs, CA). The batteries were kept on a separate side of the shipping container located away from the water systems and corrosive gases generated by the electrochlorination system. The battery compartment was also actively vented to prevent H_2 accumulation and to lower the average operating temperature of the batteries.

6.2.6 Site Installation

The site selected was a public school located in a fishermen's community in the town of Pulluvila in Kerala, India. The school had approximately 1,500 students in regular attendance spanning from 1st to 12th standard-(ranging from 6-17 year olds). The toilet area at the school was open to the general public and was located next to a large sports field which served as an important community gathering area. Every weekend and evening, football and cricket practices were held at this field. The school's primary water supply was from a well located on the school grounds. Two fully automated electronic toilets (eToilet) designed by ESS were installed at the site. The eToilets' wastewater passed through a screen pit for trash removal before entering a 2,000 liter underground equalization tank. Two tanks were installed on an adjacent building and used for the toilets' water demand. One 500 liter storage tank was used for recycled water storage, while a second tank of equal volume was used to store well water. Well water was for the hand wash basins located on the side of the eToilets as well as for the hygiene water used within the toilet. Recycled water (also referred to as product water) was used for toilet flushing and for floor pan washing which occurred after every 10 uses. The recycled water tank also had a well water connection used when recycled water was insufficient for flush water demand. The equalization tank had a total capacity of 2,000 liters. Waste water from the equalization tank was pumped directly into the AnMBR by an influent pump located within the shipping container. The final site design can be found in Figure 6.3.

Figure 6.2: Site picture showing final system as installed at the site. The two orange eToilets can be seen with their associated sinks. The AnMBR housed in a shipping container and PV system can also be seen. In the background the playing field can also be seen.

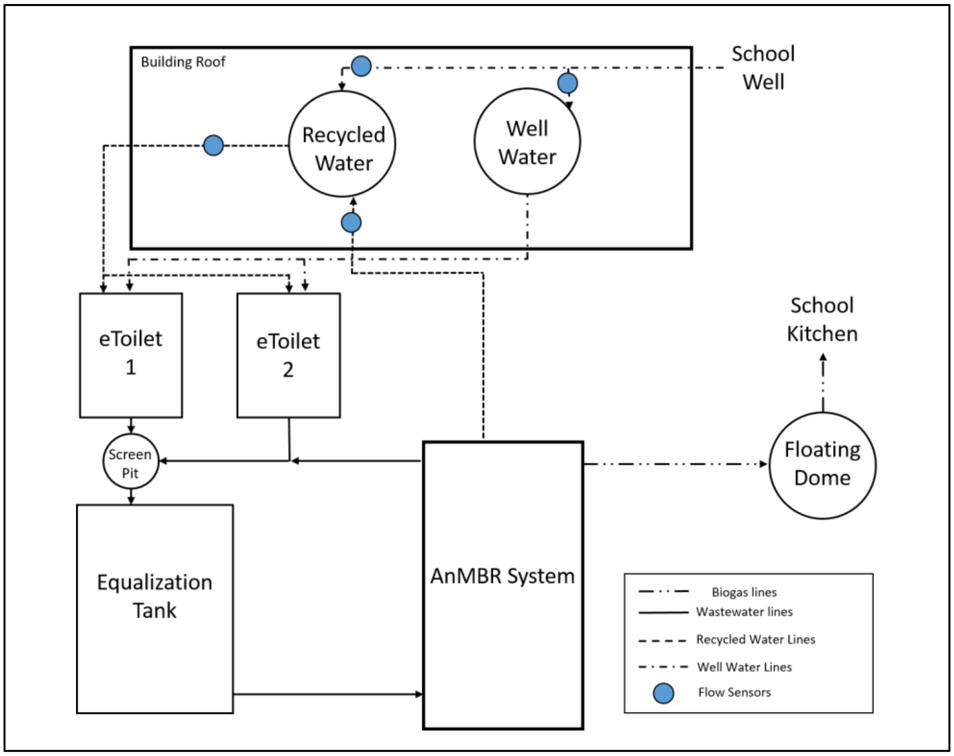

Figure 6.3: Site layout and flow sensor location details.

6.2.7 Data Collection and Control System

Two data loggers (U30 Series, ONSET, Bourne, MA) were used for continuous measurement of all sensors located at the site. One data logger, located on the roof of a building adjacent to the toilets, was used to monitor primary flows. Flow was monitored using paddlewheel flow sensors (FB151 Series, Omega Engineering, Stamford, CT) connected to the recycled water line, the well water line, and the well water line entering the recycled water storage tank. The location of these sensors can be seen in Figure 6.3. Power for the data logger and sensor array was provided for by an independent PV system. The second data logger was located within the shipping container and was used to monitor process parameters. Within the quad, all power entering and exiting the battery bank was monitored using ammeters (Hawkeye 971, Veris Industries, Tualatin, OR) located on the primary electrical lines entering and exiting the battery bank. Membrane performance was monitored using pressure transducers (Cole-Parmer, Vernon Hills, IL) located on the feed and permeate side of the membrane module. An average value for the concentrate pressure was measured using the same instrumentation, but was not monitored at the same frequency as the concentrate and permeate pressures. The shipping container, feed water, and reactor temperatures were monitored using temperature sensors. The eToilets contained their own data logging and control systems which tracked the time and number of events per day.

The operation of the AnMBR was monitored and controlled using a hobbyist microcontroller based system (Arduino, Vancouver, Canada). The control system monitored tank levels using variable resistance level sensors (Millone Tech, Sewell, NJ) and flow using paddle switches and rotary flow meters. The use of hobbyist grade microcontrollers and sensors allows for a great deal of process complexity at a low cost. Remote and low cost operation of MBRs has been described as a barrier to implementing decentralized MBRs in the past (Fane & Fane, 2005); however, with the recent advancements and proliferation of hobbyist grade microcontrollers, this challenge can be addressed as observed in this study.

6.2.8 Inoculation

For the first 28 days of operation, the system was not inoculated primarily due to the low strength of the incoming wastewater and due to hydraulic testing. On day 28, 6 liters of sludge, taken from a food waste digester run at ambient temperatures, was added to the first reactor baffle.

6.2.9 Water Quality Testing

Samples were taken from 3 points in the system, these included: the system influent, collected after the intake pump; product water, which was collected from the internal product water storage tank; a post-membrane sample, which was collected from a sample port located directly after the permeate pump. Samples were processed within 4 hours of collection. Each sample was tested for pH, turbidity, color, COD, and ammonia concentration. Turbidity and color were tested using a handheld spectrophotometer (DR9000, Hach, Loveland, CO) and color was tested at a 420 nm wave length. COD values were run in duplicates according to EPA method 410.4. Ammonia and pH were tested using ion selective probes (Neulog, Rochester, NY). Periodic analysis was conducted by an independent government research lab for total coliforms (TC), COD, and biological oxygen demand (BOD).

6.3 Results and Discussion

6.3.1 Toilet Usage

Toilet use deviated greatly from the design values. A summary of the toilet usage statistics can be seen in Table 6.2. Despite the availability of other toilet facilities at the school, the novelty and cleanliness of the two eToilets attracted high daily usage by the students. Students were often willing to wait in lines in order to use the toilets, even when other facilities were available. The toilets were popular with younger students and older girls. It was observed that younger students would often enter the toilets 4-6 at a time, which would lead to an underestimation of the usage figures. Many of the older boys would use facilities located closer to their classrooms or urinate behind buildings. The first month and a half of data collection occurred during the normal school schedule. Due to standardized testing in the month of March, many of the higher standard students did not attend school, which decreased the toilet use. The average daily usage dropped even further in the month of April due to summer vacation. During the summer, the primary users were school staff and community members using the field next to the site. The sinks on the sides of the eToilets received higher than expected usage. During normal school days, the sinks were frequently used to wash lunch containers and even cooking dishes from the school's kitchen. Water from the sinks was also used to rinse the students' sandals and for drinking purposes. Water demand profiles exhibited two distinct patterns depending on the day of the week and when the school was in session or on vacation. The weekday demand profile, which can be seen in Figure 6.4, exhibited three peak usage times at 9 AM, 1 PM, and 3 PM. These peaks in demand were related to the beginning and end of classes as well as an hour long lunch break in the middle of the day. The greatest demand, both in flush water and hygiene water was in the middle of the day after lunch. The exceptionally high hygiene water use was a result of students cleaning their dishes in the sink after lunch. The demand profile also shows that for almost 11 full hours, from 8:00 PM to 7:00 AM, there is little to no use. The weekend demand profile, seen in Figure 6.5, was much lower and had two major demand peaks at 10:00 AM and 5:00 PM. These peaks followed the arrival and departure of community members at the field next to the toilet area. During the summer break, all days began to follow the demand profile exhibited in Figure 6.5.

Table 6.2: Usage statistics for the combined use of both eToilets.

	January			February			March			April		
	Value	Std.	Max	Value	Std.	Max	Value	Std.	Max	Value	Std.	Max
Avg. Weekday Use	238	114	399	270	100	454	91	69	233	35	20	83
Avg. Weekend Use	61	31	108	155	83	287	14	12	35	28	27	78
Avg. daily Flush vol. (L)	N/A	N/A	N/A	760	578	1611	106	157	559	18	321	108
Avg. daily hygiene vol. (L)	N/A	N/A	N/A	922	637	1956	262	294	1178	54	90	260

What is significant about the user behavior is how it deviates from the design parameters and how it affects wastewater composition. The original design was for 100 uses per day, however when school was in session, the average number of weekday users was 270 with peaks as high as 454. The system should have been severely undersized for this particular application; however, as can be seen in the flow data, the average flush volume per day for the busiest period was 760 liters, which was close to the design value of 628 liters. One important note is that the variability of the water demand was quite high. The average flush volume for the entire testing period was 332 ±470 L/d, leading to a coefficient of variation of 141 %.

A higher number of users combined with a low volume of water would normally result in higher wastewater strength, but the uses were diluted with low strength hygiene water that entered the system through the sinks. As observed in previous chapters, the defecation rate at schools is also lower, which decreases the COD content and shifts the nitrogen to COD ratio of the wastewater. The resulting average COD strength of wastewater was only 109 mg/L; 25 times lower than the design value. While such a low value would make energy recovery difficult, it would allow the treatment system to accommodate a lower HRT, while maintaining a low OLR. During the design phase, sink water was not considered, as most of the previous eToilet installations did not include a hand wash basin. When considering the total flow, which included flush water and hygiene water, the average total water consumption of the combined system was 1,682 liters with a maximum total consumption of 3,567 liters.

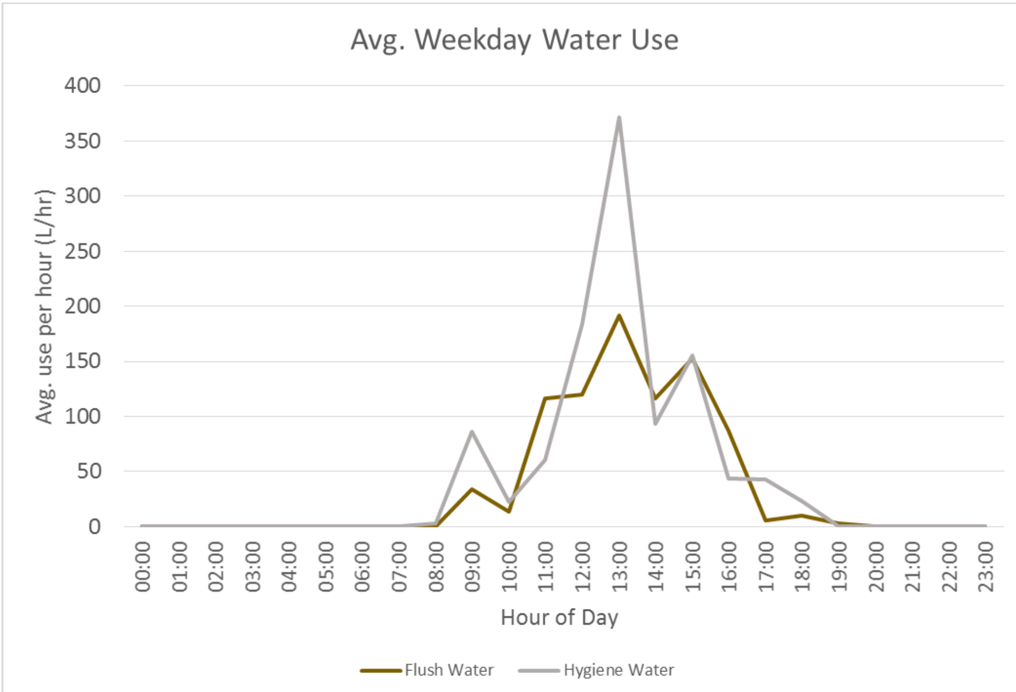

Figure 6.4: Hourly breakdown of the water demand profile during weekdays while school was in session.

Water demand, which must be met by the treatment system, is dictated by usage patterns. As can be seen from the water demand curves, the demand is not a flat rate throughout the day, but rather occurs as large peaks. This presents a problem as the AnMBR as designed, treats water at a relatively constant rate of 80 liters/hour, which is below the rate of consumption seen during peak hours. However, this problem is easily managed by increasing the total storage capacity at the site. This way the system's production capacity can be buffered by adequate storage. Understanding and using peak demand rates for storage sizing will ensure that storage is adequate in providing sufficient volumes of water even during peaks. However storage should not be overdesigned, as it increases capital costs and the footprint required by the system.

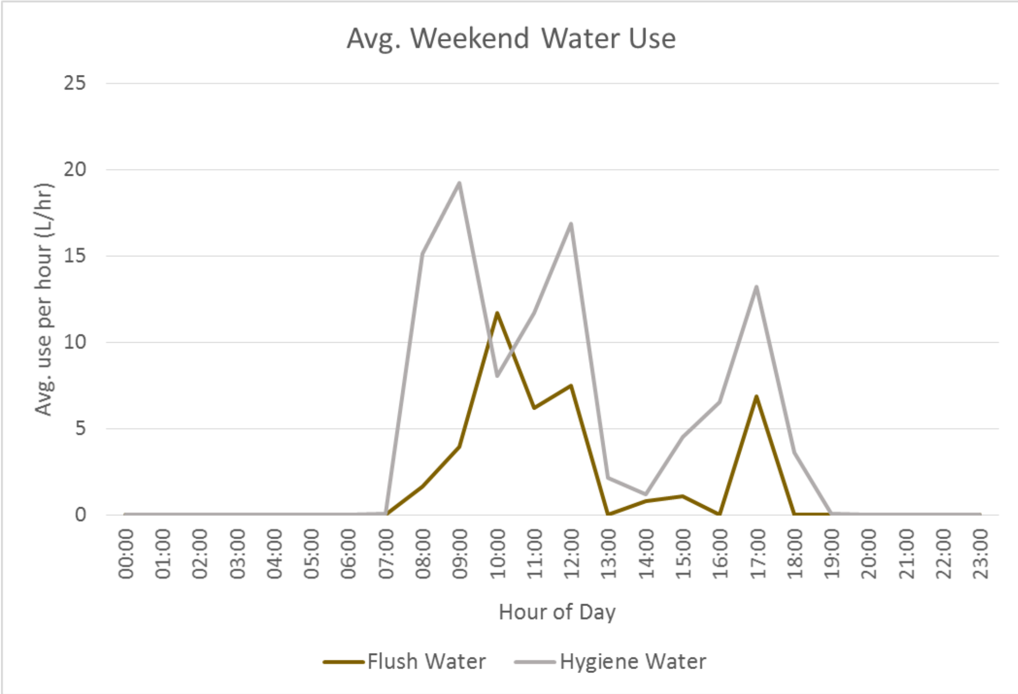

Figure 6.5: Average weekend water demand while school was in session. During the summer, all days exhibited a similar demand profile.

6.3.2 Vandalism and User Acceptance

Vandalism and theft is a concern for decentralized systems, as they are closer to the final users and operate with less immediate oversight than centralized systems. Minor vandalism occurred to the eToilets and the treatment system throughout this study, however, no event compromised the overall performance. Both systems had stickers on their outer surfaces showcasing the donors and instructions on how to operate the systems. Most stickers were removed by the students within a few days and this was a reoccurring form of vandalism observed during the study. The hydroponics system, the only external portion of the treatment system, was vandalized by students who repeatedly removed plants from the grow beds. Vandalism was observed with the sink faucets which were repeatedly broken off for the first few weeks until heavier duty taps were installed. Improving the design of the hydroponics system to make it more resilient to theft and vandalism will be required if this system is to rely on hydroponics as a treatment process. The suggestion to build a cage around the hydroponics system was presented by community members.

At this phase of the study, no specific questionnaire was conducted to measure or evaluate the overall acceptability of the combined eToilet and AnMBR system. However, observations of user behavior did indicate that the toilets were popular with older female students. This is particularly relevant, as female users are often the least satisfied and most critical with existing sanitation options in slums (Kwiringa et al., 2014). The female users also had other options located closer to their classroom that were available. Few comprehensive studies exist on the acceptability of sanitation options in slums, but those that do exist indicate that the majority of dissatisfaction of toilet facilities focus on issues of accessibility and the aesthetic characteristics of the toilet structure (Kwiringa et al, 2014; Tumwebaze et al., 2013). Users hardly ever complain or find satisfaction with the type of treatment system that is coupled to their toilet. Usually the complaints related to treatment systems are related to failures, such as pit latrines filling up (Tumwebaze et al., 2013). As summarized from Tumwebaze et al., the primary concerns of toilet users were: proximity of toilets to households, continuous accessibility of toilet unit, no visibility of the waste system contents, interior light, the ability to lock the toilet structure, cleanliness of toilet area, and a lack of heat within the unit (2013). Many, if not most of the aspects are of greatest concern to the toilet facility and don’t have direct implications on the treatment system. ESS specifically designed the eToilets to address the failures of many traditional public toilets. The two toilets installed for this study included an interior LED lighting system, a rugged locking system for user protection, and an active and passive ventilation system used to lower the temperature within the toilet structure. As one of their main features, the eToilets have a stainless steel floor pan and toilet basin which is automatically rinsed before and after each user to prevent unsanitary conditions. The water trap that is incorporated into the toilets also prevents odors and visibility of human waste. In many ways, the eToilet addresses the technical requirements for social acceptance in slum sanitation.

While sanitation systems are not typically of great interest to toilet users, they become a potential barrier to user acceptance when complete water recycling is brought into the picture. When complete water recycling is attempted, historical and cultural perspectives regarding of blackwater reuse can often prevent societal acceptance of direct reuse (Mankad and Tapsuwan, 2010). However, in that review, it was found that opinion on wastewater reuse was closely tied to the amount of direct contact between water and user. Thus, direct potable reuse of wastewater has the most negative public perceptions when compared to use as irrigation water or for toilet flushing (Mankad and Tapsuwan, 2010). In the case of this study, the only use of the recycled water was for floor pan and flush water, which would constitute reuse options that have a greater likelihood of being culturally acceptable. The perception of water scarcity is also important in determining the public's willingness to accept or reject water reuse. In countries like Australia, where drought is a historical problem, the public is accepting of water recycling (Martin et al, 2007). As slum dwellers are much closer to the problems of water availability in their cities, it is likely that they will be very familiar with water scarcity in their cities. This could potentially further influence the likelihood that they would find the technology acceptable.

6.3.3 Treatment Performance

The reactor performance, as indicated by COD, turbidity, and color removal, can be seen in Figure 6.6 through Figure 6.8. The low strength of the influent wastewater affected the total removal efficiency of the system which had an average value of about 54 %. The removal rate increased when incoming COD levels increased. The majority of the product water COD levels were below 50 mg/L. Color and turbidity removal, seen in Figure 6.7 and Figure 6.8, had much higher average removal rates of 95% and 72% during this same period.

External testing for BOD and TC is summarized in Table 6.3. As can be seen, the system was able to provide complete coliform removal. The combination of anaerobic digestion, membrane filtration and chlorination serves as a robust, multi-barrier process for removing pathogens. As the primary objective of the system was achieved, the product water is suitable for toilet flushing. Despite persistent COD in the product water, no BOD is observed. The nature of this COD should be investigated as it seems to be immune to chlorine oxidation. If the product water were to have been recycled, an accumulation of this soluble and non-biodegradable COD might occur.

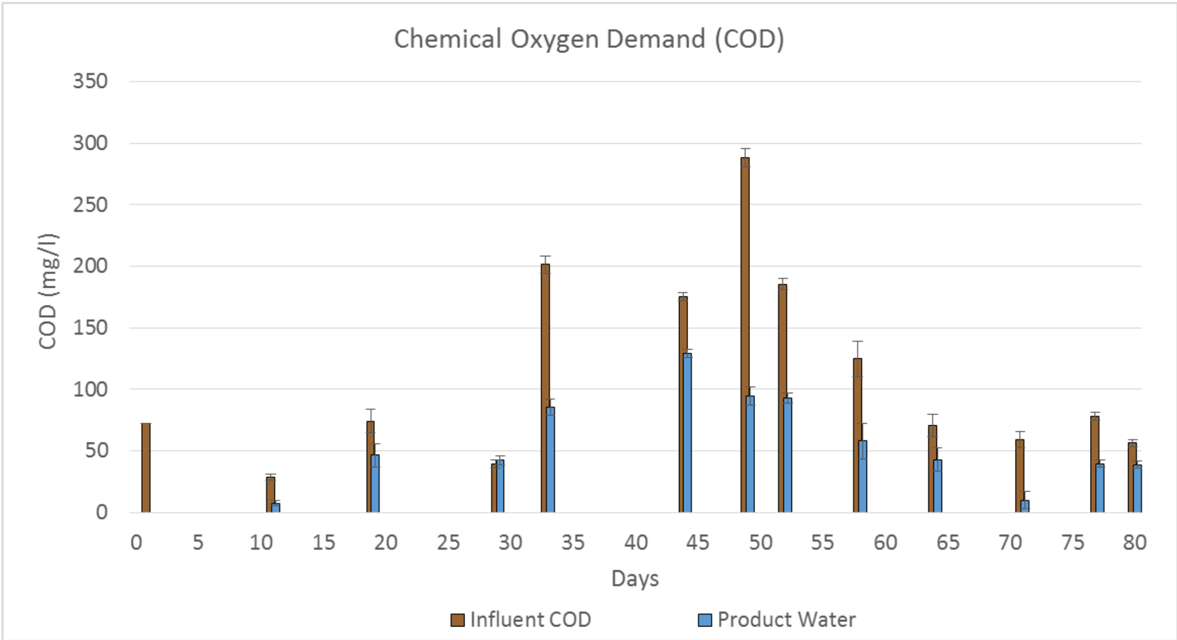

Figure 6.6: COD profiles for influent and product water during the first 4 months of operation.

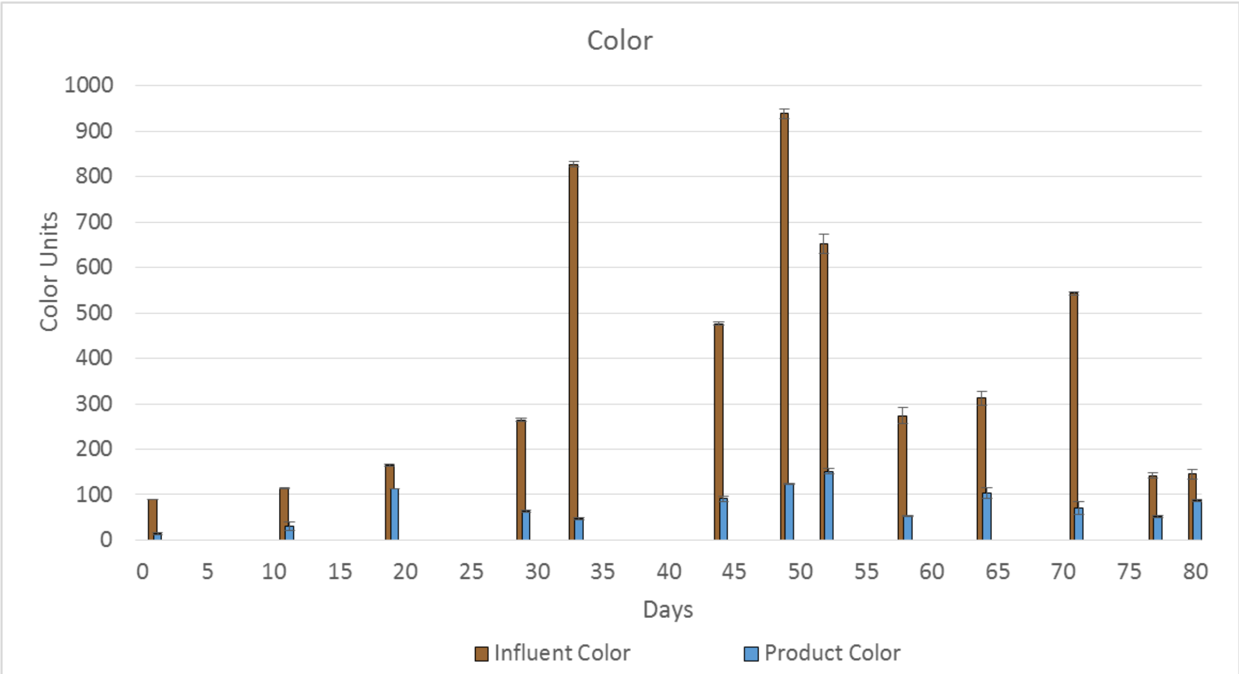

Figure 6.7: Color profile for influent and product water from the AnMBR system for the first 4 months of operation.

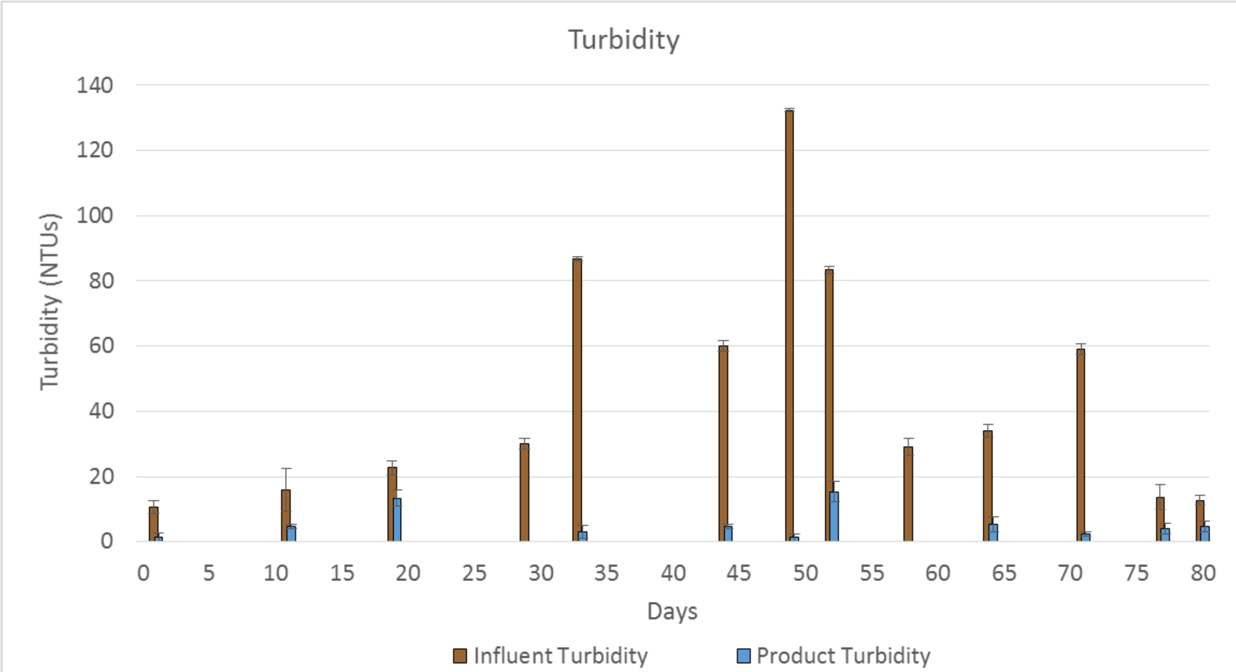

Figure 6.8: Turbidity profile for influent and product water for the first 4 months of operation.

Water quantity and production rates are also important considerations when complete water recycling is desired. The average production rate during this study was 80 liters/hour with a maximum rate of 120 liters/hr. This value varied due to changes in the composition of the permeate. Higher levels of ammonia and CODs led to longer chlorination times, reducing the rate at which the final water was produced. Using an average of 80 liters/hr, it would take 9.5 hrs to produce the maximum avg. flush water volume seen during the operational period. This means that during the highest average usage observed, the system would have 14.5 hrs per day of relaxation. When accounting for the maximum flow observed, 1,611 liters, it would take 20 hrs in a day to produce that volume. The theoretical maximum that could be produced in a 24 hr period would range from 1,920 to 2,880 liters (using the average and maximum production rates observed during this period). Using the more conservative of those figures would allow the system a greater safety factor in relation to meeting the water demand. During this period, the maximum volume produced was 1,394 liters.

Table 6.3: External testing of influent and product water for BOD and TC.

Date of Sample	Sample Point	Total Coliform Count (CFU)	BOD (mg/l)
4/6/2016	Influent	1.12 104	N/A
	Product Water	Non-detect	N/A
4/22/2016	Influent	2.98 104	26.2
	Product Water	Non-detect	0

6.3.4 Membrane Performance

A combination of low flux, short filtration times, backwashing, and frequent and long duration relaxation times, allowed the system to maintain a low TMP throughout the study. The TMP started at an average of 0.14 bar and stayed constant over the course of 4 months. This system was unique in that the membrane spent most of its time in a relaxed mode. Not only was this built into the system design, but it varied depending on water demand. During weekends, which had the lowest water demand, the membrane would often spend over 20 continuous hours in a relaxed state. Relaxation is known to serve as an effective anti-fouling method, but relaxation is often only used for a combined few minutes every day compared to almost constant filtration times. Intentionally over sizing the membrane area allows for sub-critical flux membrane operation, while still achieving the product volume required by the toilet usage. However, there is a trade-off between initial capital cost, which an over designed membrane system would entail, and the membrane's long term performance and operational costs. In this instance, focusing on low energy anti-fouling mechanisms allowed membrane fouling to be controlled without a great deal of energy use.

6.3.5 Energy Demand

The average energy use of the system per volume of final product was 1.52 kWh/m^3. However, this value was related to the total amount of water produced per day, as can be seen in Figure 6.9. When larger amounts of water were treated, the system's background energy demand accounted for a smaller fraction of total energy demand. The system's daily background demand was an average of 176 Wh. This energy was used for powering the controls, data loggers, and for active ventilation of the shipping container. Regardless if the system produced water, this background energy demand would be placed on the system. When volumes greater than 200 liters per day were produced, the average dropped to 0.83 kWh/m^3. The lowest value measured during this trial was 0.16 kWh/m^3 when 1,394 liters were produced. Filtration and system feeding accounted for approx. 52% of the energy demand while chlorination and product pumping accounted for 48% of the energy demand. A breakdown of the energy demand per cycle can be found in Figure 6.10.

In a review by Liao et al., the average energy used by an AnMBR with an external membrane module was between 3 to 7.3 kWh/m^3 while the average for a submerged module was lower at 0.25-1.0 kWh/m^3 (2006). Submerged configurations are known to have lower energy demands when compared to external, or sidestream modules (Gander et al., 2000). Since that review, other studies have worked towards minimizing the energy requirements of AnMBRs. One of the most promising advancements was a new reactor configuration, the staged anaerobic fluidized MBR (SAF-MBR) proposed by Yoo et al. (2012). In a lab-scale trial of the SAF-MBR, it was estimated that the energy requirement of the system would be 0.047 kWh/m^3 (Yoo et al., 2012). However, when this configuration was tested at the pilot scale, the energy requirement was higher at 0.23 kWh/m^3 (Shin et al., 2014). One important note regarding this system is that they did not monitor energy use, but rather estimated the use according to performance. Estimations of that sort will often underestimate the inefficiencies inherent to small-scale systems. The system in this study outperformed other external membrane modules and was only slightly higher than submerged AnMBRs when comparing the average energy demand figure. When the system is operated closer to its design value of 800-1000 L/day, its energy consumption (0.16 kWh/m^3) is even lower than that of the pilot system (0.23 kWh/m^3) presented in Shin et al., (2014). Another important consideration is that these studies are singularly focused on the reactor and membrane performance, so those values do not account for permeate polishing, control requirements, nor distribution of the final product water, all of which are accounted in the figures presented in this study.

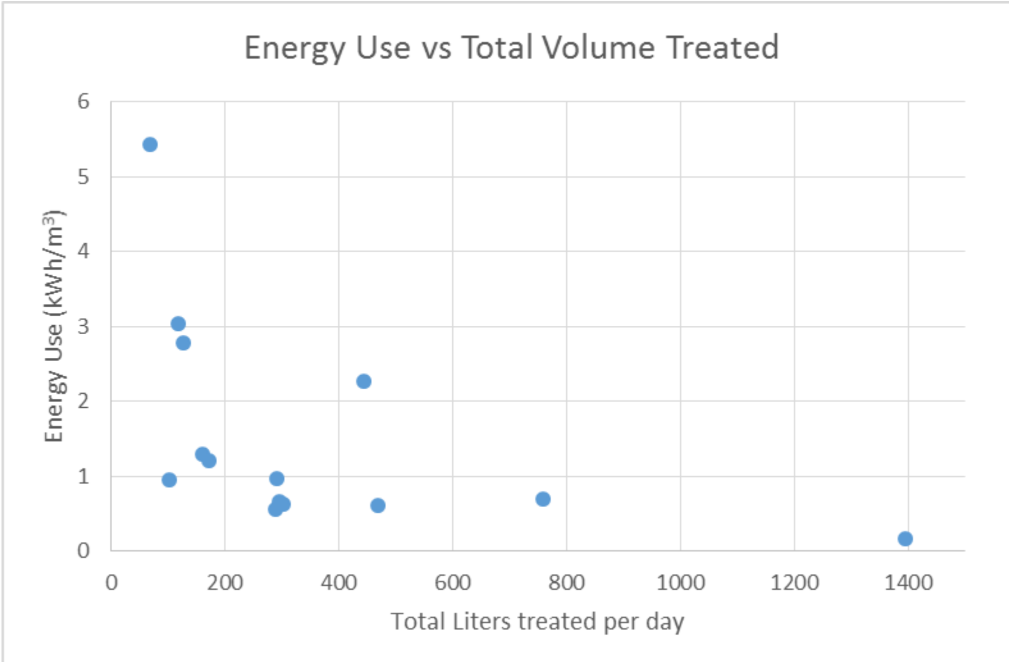

Figure 6.9: Total volume produced per day vs energy per unit volume of final product.

Through the operation of the pilot, it became apparent what processes contributed the most towards the final energy demand of the system. The current draw of each subsystem did not change throughout the study, however the duration of processes did vary. As time is important in any energy calculation, an increase in process duration would impact the final energy requirement of a subsystem. The duration of the electrochlorination system varied the most throughout the study. The duration was linked to the concentration of ammonia in the permeate. Ammonia and other nitrogen species impart a high chlorine demand, especially if breakpoint chlorination is desired. Often a 8.5-10 ratio of Cl_2 to nitrogen is required to achieve breakpoint chlorination (Randtke, 2010). With electrochlorination there is a linear relationship between energy consumption and chlorine production, so an increase in ammonia will have a linear increase in the energy consumed by the system (Randtke, 2010). More passive systems of nitrogen capture and removal should be employed if further reductions in energy demand are desired. In addition to reducing the energy demand of the system, passive removal of nitrogen would reduce the maintenance requirements and lifespan of the electrochlorinator.

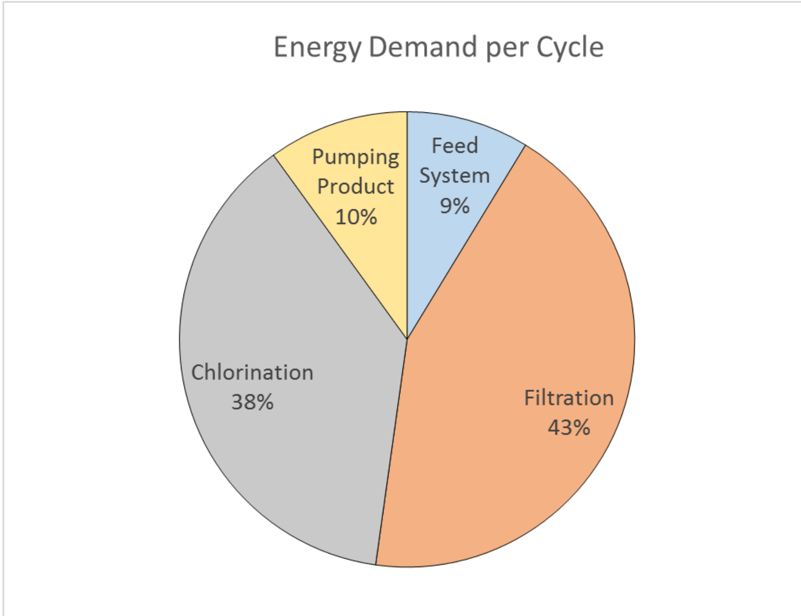

Figure 6.10: Energy breakdown per cycle for the pilot system. Background energy demand has been excluded from these values as it changes depending on the amount of cycles per day.

The system was run completely off solar energy for the duration of this study. The PV system that was designed was capable of producing far more energy than was needed for daily operation. While there is a benefit to overdesigning the PV system, future versions can benefit from reduced costs if a more appropriate system is designed.

6.4 Conclusions

A pilot scale AnMBR designed to treat human waste generated from two eToilets was constructed according to the theoretical reactor presented in Bair et al., (2015). The system was installed at a school in Pulluvila, Kerala, India and operated for a total of 4 months. During this time the system experienced two distinct periods of user behavior, one when school was in session and another during summer break. The objective of the system was to treat wastewater to the quality and quantity required for toilet flushing. In the course of this study, the following observations and conclusions were made:

- Toilet usage rates were higher than predicted with an avg. of 270 uses per day during the school season producing 760 liters of low strength wastewater. The variability of usage was also very high, with peaks of 454 users per day producing up to 1,611 liters of wastewater.

- Daily usage followed two main trends, a weekday and weekend trend. Daily usage was limited to the hours of 7 AM through 7 PM, allowing the system to catch up to the demand in the evenings and switch to standby during nights.
- Vandalism was observed during the study, but it did not affect the treatment system's performance or ability to achieve its primary objective. However, a redesign of the hydroponics system will be required if it is to serve an integral part of the system's performance in the future.
- During the first four months, the system had a mediocre avg. COD removal of 54%. This low figure is primarily a result of the low incoming COD strength and a persistent and low level of COD found in the product water. The system did achieve high rates of color and turbidity removal as well as complete coliform removal.
- A combination of low-energy anti-fouling mechanisms including sub-critical flux operation, short filtration times, backwashing, and frequent and long relaxation modes allowed the system to be operated for 4 months at a TMP of 0.14 bar.
- The system's average energy consumption per unit volume treated was 1.52 kWh/m^3, however that value depended greatly on the total amount of water produced per day. When over 200 liters were produced per day, this avg. dropped to 0.83 kWh/m3.

Together these results show that an off-grid AnMBR can used for full water recycling in a high density environment.

6.5 References

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Chapter 7: Conclusions and Future Work

7.1 Conclusions

When taken from a global perspective, sanitation remains a blight on humanity. Despite large investments and global initiatives aimed at tackling sanitation problems, a large percentage of global society still lacks access to adequate sanitation. As countries around the world urbanize, sanitation problems are concentrated in the rapidly growing cities of developing countries. These cities, often not able to accommodate the population growth, experience an unregulated expansion of high-density informal housing settlements. These areas often lack public infrastructure and are uniquely challenging environments for traditional sanitation technologies. The high user rates, lack of water and electricity infrastructure, space limitations, and scant financial resources combine to cause premature failure to most decentralized sanitation facilities in these areas. New and more appropriate technologies need to be developed for these challenging areas.

Membrane bioreactor (MBR) technology is routinely used in the developed world when a compact and resilient treatment system is needed. However, most MBRs utilize aerobic treatment, which demands high energy use. The energy demand can render the technology inappropriate in areas where electricity might be unreliable or costly. The development of anaerobic MBRs (AnMBR), which do not require aeration, has led to a significant improvement of the energy profile of MBRs. AnMBR research is still in its early stages and questions abound regarding the technology's applicability in high-density urban environments. This body of research is aimed at understanding the AnMBR's treatment performance and overall robustness in challenging circumstances similar to those that would be encountered in slums.

The appropriateness of AnMBR was tested with a number of pilot scale systems treating real wastewater in the field. The first test, discussed in Chapter 3, was used to determine the resilience of

AnMBR treatment during high variations of feed composition and periods of disuse. Decentralized systems often see much higher variations in feed composition than centralized systems as they lack an extensive collection system which homogenizes the influent wastewater. Depending on the application, periods of no flow are also possible. The ability to return to regular high flow conditions following a period of disuse is important for the flexibility of decentralized AnMBRs. During this long-term study it was apparent that the membrane served an important role in controlling the effluent quality, especially when environmental conditions and feed characteristics varied so significantly as to upset biological stability. The system was capable of COD removal efficiencies of over 88.2% throughout the study. It was also observed during this study that the system had higher removal efficiencies when treating higher COD concentrations. Higher strength wastewaters can routinely be found in decentralized applications where dilution water is minimal. These locations include water-efficient buildings, direct coupling to public toilets, and fecal sludge treatment plants. It was also found that the AnMBR was capable of rapidly recovering from extended periods of disuse. This ensures that the AnMBR can be applied to areas, such as schools and hotels that experience large seasonal variations and periods of disuse.

The second experiment, described in Chapter 3, looked at how fluctuations in ambient temperatures would affect the interaction between biological treatment and membrane fouling. Controlling the operating temperature of a decentralized AnMBR would incur a high energy demand, which would make the technology less appealing for application with dilute waste streams. Allowing the reactor to operate at ambient temperatures means that variations can be high, and that operating temperatures can drop below ideal ranges. Temperature is known to affect biological treatment and to a lesser extent membrane filtration, but the interactions between the two are understood to a lesser extent. To determine the effect of temperature on operation, a pilot scale AnMBR was used to treat wastewater with fluctuating ambient temperatures. Three trials were conducted during summer and winter conditions, as well an artificially heated period. It was found that membrane permeability can be greatly affected by operating temperature but its effect varied depending on the fouling state of the membrane. Virgin, or recently cleaned membranes were not affected by low temperatures, while the permeability of slightly fouled membranes was negatively correlated to changes in temperature. When slightly fouled, a membrane TMP could increase by 2.4 times with a 10ºC drop in temperature. The magnitude of the TMP increase could not be explained by changes in water viscosity. The effect of temperature on TMP decreased when fouling became severe and normal operating pressures were high. These results suggest that seasonal adjustments to AnMBR operation would be necessary to prevent sharp and excessive increases in operational TMP during cold spells.

Chapter 4 looked at the feasibility of recovering water, nutrients, and energy in an off-grid and decentralized AnMBR. This investigation ran an energy, nutrient, and mass balance for a theoretical AnMBR treating water from a public toilet in a high density setting. What was concluded from this study is that complete water recycling could be accomplished onsite and on a small scale. Onsite water recycling would allow for the system to be applied in arid urban areas as well as places lacking regular water provision. The study also concluded that the energy content of wastewater in a high density area would be sufficient to power an AnMBR and electronic toilet. For areas where low wastewater strengths would be expected, food waste addition to the wastewater would improve the energy profile of the system. As many urban areas of developing countries struggle with solid waste management, there is the opportunity to link food waste management with wastewater treatment. This study also highlighted the potential problems that ammonia and salinity buildup could have on a system that achieves complete water recycling.

Once the system specifically designed for urban areas was deemed theoretically feasible, a full-scale pilot system was constructed and tested. This system, which was applied in Kerala, India, was investigated for its treatment and membrane performance as well as energy consumption. The TRL 7 system consistently produced product water with low COD, color and odor. The product water was adequate for toilet flushing purposes. The wastewater strength was much lower than anticipated, mainly due to the system’s application in a school setting and due to high dilution water. The reliance on multiple anti-fouling mechanisms allowed the system to operate for 4 months without a significant change in TMP. The average energy consumption per unit of produced water depended on the amount of water treated per day. On average the energy consumption was 1.52 kWh/m^3, but that value dropped to 0.83 kWh/m^3 when volumes greater than 200 liters were treated per day. All of the energy used by the system was produced by onsite photovoltaics. While the system was capable of meeting the water demand of the toilet system, improvements in the energy demand of the system will be necessary to make the system more cost effective.

When taken together, the results suggest that AnMBRs can be an appropriate sanitation technology for high density urban areas. The ability to handle large fluctuations in feed concentration, volume, and temperatures suggests they are appropriate for decentralized applications. Their reliable treatment performance, which is ensured by membrane filtration, allows water to be recycled onsite with minimal operator oversight. The low energy requirements of the system allow for onsite renewable energy sources to be used to power the device. AnMBRs are able to address many of the challenges that traditional sanitation technologies cannot, which makes them far more appropriate for addressing the problems of slum sanitation.

7.2 Future Work

This body of work addresses many of the technological challenges related to AnMBR design and operation, however there are other non-technical barriers that were not addressed. Economic and cultural challenges to implementation need to be further investigated. Cost is an important factor which can ultimately determine the applicability of AnMBRs in slums. High CAPEX or OPEX can render the technology nonviable for areas with limited budgets. Further system optimization and value engineering will be required to reduce the final cost of implementation. Aside from direct costs, investigating the necessary political and financial framework necessary for implementation will be vital to scaling up the technology. In most cases, the final users cannot be the sole payers for sanitation, which requires creative business models to leverage public/private partnerships for project development and maintenance. Understanding the financial framework will also help dictate the most appropriate scale at which the technology can be applied.

Another non-technical challenge that needs to be further studied and addressed is the social acceptance of onsite water recycling amongst final end users. This is vital to the technology's success as technology adoption and maintenance by the local community is vital to the longevity of any sanitation project or program. This concern is of great importance as some communities may not find the practice acceptable, even when the reuse is limited to toilet flushing. Other social factors including the desirability of the system need to be understood and leveraged to improve the acceptance of the technology.

Additional technical challenges remain, such as with the effect of salt accumulation in the recycled water. Salts entering the system through urine are not removed or retained by the biological process, so complete recycling of the water will lead to salt accumulation. The extent of accumulation and its effects on the biological treatment will need to be investigated further. Improvements in system design, particularly with passive nitrogen removal will be necessary to reduce the energy consumption of the treatment unit. Reducing the energy required for treatment will in turn, reduce the final cost of the unit by reducing the size of the PV collection and battery storage system. Additional system optimization needs to occur to further reduce the footprint required by the unit while maximizing the product water output.

Appendices

Appendix A. Supplementary Information for Chapter 3

What follows is a more detailed description of the reactor used for experimentation in Chapters 3 and 4. The entire system was built to be contained inside of a tool cabinet which also served as the structural component to which pumps and vessels were attached. The original 3D design can be found in Figure A1. The system as constructed can be found in Figure A2. While the majority of permeate produced by this system was sent back to the septic tank, some permeate was routed towards algal growth and a hydroponics system located at the school. An image of the hydroponics system can be found in Figure A3. Additional permeate was routed towards algal cultivation in a photobioreactor, found in Figure A4. Both the hydroponics and photobioreactors served as demonstration units for the students at the school of novel bio recycling principles.

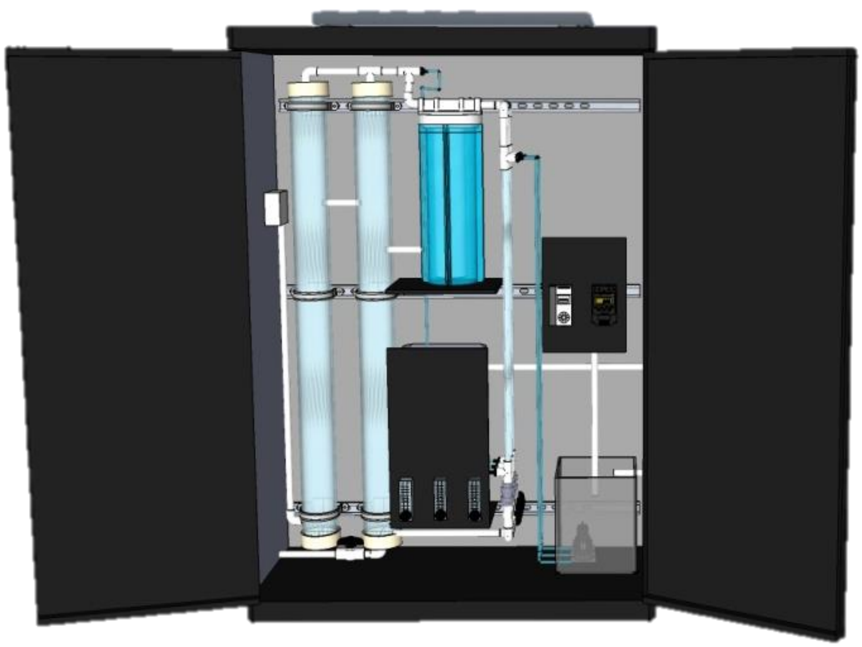

Figure A1: Original 3D computer design of the AnMBR used in chapters 3 and 4.

Figure A2: Front view of AnMBR system as built and tested in chapters 3 and 4.

Component list from Figure A2 is as follows:

1. Reactor 1 (R1)
2. Reactor 2 (R2)
3. Gas-liquid separator
4. Head space sampling point
5. Wet Tip meter (WTM)
6. Control and indicator box
7. Permeate lines
8. Pump Control module housing
9. Permeate counting system
10. Backwash tank
11. Membrane feed connector
12. Feed pump

Figure A3: The Biorecycing & Bioenergy Research and Training Station (BBRATS) at Learning Gate Community School. From left to right are: hydroponic greenhouse, shed housing TRL6 AnMBR, and algal photobioreactors.

Figure A4: Hydroponics system located in green house adjacent to TRL 6 system. Permeate from the AnMBR was used for an initial study into the plant growth.

Figure A5: Algal photobioreactors located at the entrance of the shed containing the TRL 6 AnMBR. Permeate from the system was used for this demonstration unit for algal growth.

Appendix B. Supplementary Information for Chapter 5

This appendix includes additional tables that were not included in the original manuscript for Chapter 5. The tables include additional inputs to the model and the outputs of the model.

Table B1: Additional energy parameters and inputs used to model the AnMBR performance.

Energy		
Parameter	Value	Units
COD Electron Equivalent	0.125	mol e/g COD
Avogadro's Number	6.02E+23	e/mol
Ampere Electron Equivalent	6.24E+18	e/s
Biosystem (MFC) Voltage Capacity	1.2	V
fe	0.95	-
% CH4 in Biogas	65%	-
CH4 Yield	0.350	L CH4/g COD
Heating Value of CH4	52.8	kJ/g
Biogas Mean Molecular Weight	25.8	g/mol
Daylight Hours (Winter)	4	h
Daylight Hours (Avg.)	6.5	h
Solar PV Yield	193.17	W/m2
Solar PV Performance Ratio	0.7	-
Gravitational Acceleration	9.81	m/s2
Density of Wastewater	1.01	kg/L
kPa to m water column	0.101971621	m/kPa
atm to kPa	101.325	kPa/atm
Gas Volume for Sparging	0.05	m3 gas/m3 water
Pressure in Reactor Headspace	1.2	atm
	121.59	kPa
Biogas Pressure Loss Through Membrane Unit	30	kPa
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/m2/d
Solar Insolation (Winter)	4.8	kWh/m2/d
Solar Thermal Efficiency	65%	-
Solids Drying Energy Requirement	3.605	kJ/g
Efficiency of Solids Drying	0.75	-
Heating Value of Dried Solids (Biomass and Trash)	12	kJ/g

Table B2: System mass balance outputs.

Mass Balance (100% eToilet)				
Toilet Solids Inflow	1.10	kg/d	100.0	%
Urinary	0.25	kg/d	22.3	%
Fecal	0.60	kg/d	54.9	%
Trash	0.25	kg/d	22.8	%
Toilet Solids Outflow	1.10	kg/d	100.0	%
NEWgen Screenings	0.24	kg/d	21.6	%
NEWgen Solids Inflow	0.86	kg/d	78.4	%
NEWgen Biogas	0.29	kg/d	26.3	%
CH4	0.19	kg/d	17.1	%
CO2 and Other Gases	0.10	kg/d	9.2	%
NEWgen Nutrient Recovery	0.22	kg/d	19.7	%
NEWgen Recycle Flow	0.01	kg/d	1.0	%
NEWgen Zeolite Recovery	0.15	kg/d	13.4	%
NEWgen Chlorination Removal	0.02	kg/d	1.5	%
NEWgen Reactor Waste Solids	0.18	kg/d	16.4	%
Ash After Solids Processing	0.04	kg/d	3.8	%
Flue Gas (excluding Air Input)	0.66	kg/d	60.5	%
Accumulation = Inputs - Outputs	0.00	kg/d	0.0	%
Mass from Users to eToilet	1.10	kg/d	100.0	%
Mass from eToilet to NEWgen	1.10	kg/d	100.0	%
Mass from NEWgen as Fertilizer	0.36	kg/d	33.1	%
Mass from NEWgen as Ash	0.04	kg/d	3.8	%
Mass from NEWgen as Flue Gas	0.66	kg/d	60.5	%
Mass from NEWgen to eToilet as Recycle Flow	0.01	kg/d	1.0	%
Mass from NEWgen as Chlorination Removal	0.02	kg/d	1.5	%

Table B3: System carbon balance.

Carbon Balance (100% eToilet)				
eToilet Inflow	315.7	g/d as C	100.0	%
Urinary	32.5	g/d as C	10.3	%
Fecal	233.1	g/d as C	73.9	%
Trash	50.0	g/d as C	15.8	%
eToilet Outflow	315.7	g/d as C	100.0	%
NEWgen Inflow	315.7	g/d as C	100.0	%
NEWgen Biogas	167.9	g/d as C	53.2	%
CH4	140.4	g/d as C	44.5	%
CO2 and Other Gases	27.5	g/d as C	8.7	%
NEWgen Nutrient Recovery	0.0	g/d as C	0.0	%
NEWgen Screenings	47.5	g/d as C	15.0	%
NEWgen Recycle Flow	0.0	g/d as C	0.0	%
NEWgen Zeolite Recovery	10.4	g/d as C	3.3	%
NEWgen Chlorination Removal	0.0	g/d as C	0.0	%
NEWgen Reactor Waste Solids	89.9	g/d as C	28.5	%
Ash After Solids Processing	13.7	g/d as C	4.4	%
Flue Gas (excluding Air Input)	291.5	g/d as C	92.4	%
Accumulation = Inputs - Outputs	0.0	g/d as C	0.0	%
Mass from Users to eToilet	315.7	g/d as C	100.0	%
Mass from eToilet to NEWgen	315.7	g/d as C	100.0	%
Mass from NEWgen as Fertilizer	10.4	g/d as C	3.3	%
Mass from NEWgen as Ash	13.7	g/d as C	4.4	%
Mass from NEWgen as Flue Gas	291.5	g/d as C	92.4	%
Mass from NEWgen as Chlorine Removal	0.0	g/d as C	0.0	%
Mass from NEWgen to eToilet as Recycle Flow	0.0	g/d as C	0.0	%

Table B4: Nitrogen balance for AnMBR.

Nitrogen Balance (100% eToilet)				
eToilet Inflow	169.8	g/d as N	100.0	%
Urinary	134.8	g/d as N	79.4	%
Fecal	30.0	g/d as N	17.7	%
Trash	5.0	g/d as N	2.9	%
eToilet Outflow	169.8	g/d as N	100.0	%
NEWgen Inflow	169.8	g/d as N	100.0	%
NEWgen Biogas	0.0	g/d as N	0.0	%
CH4	0.0	g/d as N	0.0	%
CO2 and Other Gases	0.0	g/d as N	0.0	%
NEWgen Nutrient Recovery	152.4	g/d as N	89.8	%
NEWgen Screenings	4.8	g/d as N	2.8	%
NEWgen Recycle Flow	0.0	g/d as N	0.0	%
NEWgen Zeolite/Chlorination Process	0.0	g/d as N	0.0	%
NEWgen Reactor Waste Solids	12.6	g/d as N	7.4	%
Ash After Solids Processing	1.7	g/d as N	1.0	%
Flue Gas (excluding Air Input)	15.6	g/d as N	9.2	%
Accumulation = Inputs - Outputs	0.0	g/d as N	0.0	%
Mass from Users to eToilet	169.8	g/d as N	100.0	%
Mass from eToilet to NEWgen	169.8	g/d as N	100.0	%
Mass from NEWgen as Fertilizer	152.4	g/d as N	89.8	%
Mass from NEWgen as Ash	1.7	g/d as N	1.0	%
Mass from NEWgen as Flue Gas	15.6	g/d as N	9.2	%
Mass from NEWgen as Chlorine Removal	0.0	g/d as N	0.0	%
Mass from NEWgen to eToilet as Recycle Flow	0.0	g/d as N	0.0	%

Table B5: Energy balance of AnMBR.

Energy Balance, Average (100% eToilet)				
Energy from Users (Includes Trash)	4.292	kWh/d	32.2	%
Energy from Users After Losses	2.470	kWh/d	18.5	%
Energy from Users Lost	1.822	kWh/d	13.7	%
Solar Electric Generation	7.199	kWh/d	54.0	%
Solar Thermal Generation	1.846	kWh/d	13.8	%
Total Solar Energy Generation	9.045	kWh/d	67.8	%
CHP Electric Generation	1.010	kWh/d	7.6	%
CHP Thermal Generation	1.460	kWh/d	10.9	%
NEWgen Electric Demand	0.405	kWh/d	3.0	%
Liquid Pumping	0.182	kWh/d	1.4	%
Gas Sparging	0.223	kWh/d	1.7	%
NEWgen Thermal Demand	3.306	kWh/d	24.8	%
Feed Preheating	2.748	kWh/d	20.6	%
Solids Drying	0.558	kWh/d	4.2	%
NEWgen Total Demand	3.710	kWh/d	27.8	%
Toilet Electric Demand	1.800	kWh/d	13.5	%
Accumulation (Electric)	6.004	kWh/d	45.0	%
Total Electric Generation	8.208	kWh/d	61.6	%
Total Electric Demand	2.205	kWh/d	16.5	%
Accumulation (Thermal)	0.000	kWh/d	0.0	%
Total Thermal Generation	3.306	kWh/d	24.8	%
Total Thermal Demand	3.306	kWh/d	24.8	%
Accumulation = Inputs - Outputs	6.004	kWh/d	45.0	%
Energy from Users to Toilet	4.292	kWh/d	32.2	%
Energy from Toilet to NEWgen	4.292	kWh/d	32.2	%
Energy from Toilet as Toilet Demand	1.800	kWh/d	13.5	%
Energy from NEWgen as Uncaptured Energy	1.822	kWh/d	13.7	%
Energy to NEWgen as Solar	9.045	kWh/d	67.8	%
Energy from NEWgen to Toilet as Recycle Flow	1.800	kWh/d	13.5	%
Energy from NEWgen as Electricity	6.004	kWh/d	45.0	%
Energy from NEWgen as NEWgen Demand	3.710	kWh/d	27.8	%

Table B6: Water balance of AnMBR

Water Balance (100% eToilet)				
Toilet Inflow	389.3	L/d	100.0	%
Urinary	17.2	L/d	4.4	%
Fecal	2.2	L/d	0.6	%
Pre-Flush	65.0	L/d	16.7	%
Flushing	140.0	L/d	36.0	%
Platform Cleaning	65.0	L/d	16.7	%
Personal Hygiene	100.0	L/d	25.7	%
Loss via User Contact and Splashing	17.5	L/d	4.5	%
Toilet Outflow	371.8	L/d	95.5	%
NEWgen Inflow	371.8	L/d	95.5	%
NEWgen Biogas	0.3	L/d	0.1	%
NEWgen Solids Processing	2.8	L/d	0.7	%
NEWgen Recycle Flow	368.7	L/d	94.7	%
Required Makeup Flow	1.3	L/d	0.3	%
Water Production	0.0	L/d	0.0	%
Total System Inflow (Ng+T)	20.7	L/d	5.3	%
Total System Outflow (Ng+T)	20.7	L/d	5.3	%
Accumulation = Inputs - Outputs	0.0	L/d	0.0	%
Water from Users to Toilet	19.3	L/d	5.0	%
Water from to Toilet as Makeup	1.3	L/d	0.3	%
Water from Toilet to NEWgen	371.8	L/d	95.5	%
Water from Toilet as Losses	17.5	L/d	4.5	%
Water from NEWgen as Losses	3.1	L/d	0.8	%
Water from NEWgen to Toilet as Recycle Flow	368.7	L/d	94.7	%

Appendix C. Supplemental Information for Chapter 6

What follows is supplementary information related to the construction and operation of the TRL 7 AnMBR described in Chapter 6. The system was constructed and hydraulically tested at USF’s Tampa campus during the summer of 2015. During this testing stage, temporary external tanks were used in place of the equalization and product water tanks. Only clean water was used during the testing at USF. Solar thermal heating of the influent was incorporated at this stage, but was subsequently removed due to poor performance during hydraulic testing. Figure C1 and Figure C2 show the unit during testing at the USF.

Figure C1: TRL 7 unit with incorporated hydroponics being hydraulically tested at the USF’s Tampa Campus.

Figure C2: Doors open on the TRL 7 system. In the background the ABR can be seen, while in the foreground on the left the chlorination tank and system

Once the system was tested at USF, it was packaged and shipped to India. While it was on route, site prepartation was conducted by ESS (See Figure C3). The two eToilets located at the site were installed at the site approximately 3 weeks prior to the treatment system's installation. During this time, an overflow from the equalization was installed to prevent an equalization tank failure. The overflow from the equalization tank led to a leach pit located next to the equalization tank. The TRL 7 arrived at the site on the last week of December, 2015. Full installation and integration was accomplished by early January. An overhead shot of the final site can be found in Figure C4.

Figure C3: Site preparation and civil work prior to TRL 7 installation. The foundations for the eToilets as they were installed.

Figure C4: Overhead view of the site as installed during the initial month of testing for Chapter 6.

Figure C5: Familiarization of the system with school teachers and staff.

Appendix D. Water Reuse Standards

D.1 Water Resuse Standards

Drinking water and wastewater treatment is monitored and regulated by India's Central Pollution Control Board (CPCB), which falls under the Ministry of Environment and Forests. While wastewater reuse is an area of growing interest in India, there is little in terms of regulations related to reuse. Table D1 shows the specific discharge standards set by the CPCB as they relate to final discharge locations. Within these, land irrigation is the only example of a standard set for water reuse. For land irrigation the limits on water quality are not very stringent with suspended solids being as high as 200 mg/L and with BOD_3 levels as high as 100 mg/L. As toilet flushing is not specifically covered by any of the discharge limits of the CPCB, this project looked at drinking water standards also set by the CPCB. Those standards can be found in Table D2.

Table D1: National Indian wastewater discharge limits. Some parameters which are specific to industrial wastes have been omitted. Table adapted from CPCB (n.d.).

Parameter	Inland Surface Water	Public Sewers	Land for Irrigation	Marine Coastal Areas
SS (mg/L)	100	600	200	
pH	5.5-9	5.5-9	5.5-9	5.5-9
Ammonical nitrogen (as N) (mg/L)	50	50	--	50
Free Ammonia (as NH3)	5	--	--	5
BOD_3 (mg/L)	30	350	100	100
COD (mg/L)	250	--	--	250

Table D2: Water quality criteria of the CPCB. A is drinking water source without conventional treatment but after disinfection; B is outdoor bathing water; C is drinking water source after conventional treatment and disinfection; and D is water used for wild life and fisheries. Table adapted from CPCB, (2007).

Parameter	A	B	C	D
Total Coliforms (MPN/100ml)	50 or less	500	5000	--
pH	6.5 - 8.5	6.5 – 8.5	6 – 9	6.5 – 8.5
DO (mg/L)	6	5	4	4
BOD_5 (mg/L)	2	3	3	--
Ammonia (mg-N/L)	--	--	--	1.2

Within the drinking water standards there are no specific guidelines or suggested applications beyond the four categories presented in Table D2. In other words, it is not specifically stated if the water suitable for bathing (Category B) is permitted for toilet flushing or for other urban reuse applications. However, the level of intimate contact between users and bathing water would suggest that meeting bathing water standards should be more than sufficient for toilet flushing water. Due to the lack of development with India's water reuse regulations, standards from countries with a longer history of reuse were investigated.

In the United States of America, water reuse guidelines are broken down according to their final application. Toilet flushing, as well as urban irrigation in areas that cannot restrict the public's access fall under the category of "unrestricted urban reuse." There are seven states that have specific standards for this category. Their standards are summarized in Table D3. While some parameters vary within these categories, the emphasis is on microbial indicators, specifically fecal and total coliforms. There is also an important reliance on turbidity, however this is often used as a surrogate for suspended solids and overall treatment performance.

Table D3: Unrestricted urban reuse standards of US states. Adapted from (EPA, 2004)

	Arizona	California	Florida	Hawaii	Nevada	Texas	Washington
BOD$_6$	--	--	20 CBOD$_5$	--	30	5	30
TSS (mg/L)	--	--	5.0 mg/L	--	--	--	30
Turbidity (NTUs)	2 (avg)	2 (avg)	--	2 (max)	--	--	2 (avg)
	5 (max)	5 (max)			--		5 (max)
Coliform	Fecal	Total	Fecal	Fecal	Fecal	Fecal	Fecal
	ND (avg)	2.2/100 ml (avg)	75% of samples ND	2.2/100 ml (avg)	2.2/100 ml (avg)	20/100 ml (avg)	2.2/100 ml (avg)
	23/100 ml (max)	23/100 ml (max in 30 days)	25/100 ml (max)	23/100 ml (max in 30 days)	23/100 ml (max)	75/100 ml (max)	23/100 ml (max)

D.2 References

CPCB, (n.d.). General standard – Central Pollution Control Board. Retrieved from http://cpcb.nic.in/GeneralStandards.pdf.

CPCB, (2007) Water quality criteria. Retrieved from http://www.cpcb.nic.in/Water_Quality_Criteria.php.

EPA, U. (2004). Guidelines for water reuse EPA.

Appendix E. Broader Impacts: Teach Engineering Documents – Biological Processes [4]

Subject Areas: biology, chemistry, natural sciences, science & technology

Associated Unit: N/A

Lesson Title: Biological Processes: Putting Microbes to work.

Grade Levels: 5 (3 – 12)

Time Required: 2 class period – 30 minutes

For extended activity: 4-5 weeks

Summary:

Students will learn the fundamentals of using microbes to treat wastewater. The students will understand how wastewater is generated and its primary constituents. Microbial metabolism, enzymes and bioreactors will be explored to fully understand the primary processes occurring within organisms.

Engineering Connection:

Environmental engineers use biological processes to accomplish a variety of environmentally important tasks including wastewater treatment, soil remediation, aquifer remediation and drinking water treatment. Understanding the way that microorganisms grow can help engineers develop more efficient treatment systems.

Keywords:

Bioreactor, wastewater, biological process, microorganisms, growth curve

Educational Standards:

Florida, Science, 2009, SC.3.P.10.3: Demonstrate that light travels in a straight line until it strikes an object or travels from one medium to another.

Florida, Science, 2009, SC.4.E.6.5: Investigate how technology and tools help to extend the ability of humans to observe very small things and very large things.

Florida, Science, 2009, SC.4.L.17.4: Recognize ways in which plants and animals, including humans, can impact the environment.

Florida, Science, 2009, SC.5.E.7.5: Recognize that some of the weather-related differences, such as temperature and humidity, are found among different environments, such as swamps, deserts, and mountains.

Florida, Science, 2009, SC.5.L.17.1: Compare and contrast adaptations displayed by animals and plants that enable them to survive in different environments such as life cycles variations, animal behaviors and physical characteristics.

Learning Objectives

After this lesson, students should be able to:

- Characterize wastewater constituents and define its points of origin.
- Describe what happens when raw wastewater is disposed of in natural bodies of water.
- Identify biological processes as the primary method of cleaning water.

Figure E1: Title page of Teach Engineering document

[4] The contents of this chapter are published in: R. Bair, P. Rochas, T. Das, D. L. Martinez. 2012. Biological Processes: Putting Microbes to work. TeachEngineering Digital Library. Dec. 12, 2012. The document can be found at: http://www.teachengineering.org/view_lesson.php?url=collection/usf_/lessons/usf_microbes/usf_microbes_lesson01.xml.

- Define key words like enzyme and bioreactor.
- Identify the 5 stages of growth experienced by microorganisms.

Introduction/Motivation:

Have you ever wondered what happens to your waste when you flush a toilet? Have you ever considered what happens to all the soaps and detergents that go down your drain? Most people like to keep themselves blissfully ignorant of the fate of their waste. Yet, how we deal with our waste is of vital importance because of its potentially negative effects on the environment and human health. Wastewater can be a large source of pathogens and pollution. Environmental engineers focus on cleaning up wastewater before it is released back into the environment. In their pursuit of clean water, they have helped bridge many fields of science including traditional engineering, chemistry and biology. This module will explore the use of biological process in treating wastewater, as well as give a few examples of biological systems use in other fields.

Lesson Background and Concepts for Teachers:

<u>Wastewater:</u>

Wastewater is produced once water has been used and contaminated with other substances. Every society that has ever existed has produced wastewater. In a city, wastewater can come from domestic, industrial and agricultural sources. Domestic sources include stores, houses and even parks. Within a house all the water that goes into the sewer system is considered wastewater. This includes water from showers, sinks, washer machines and toilets.

Industrial sources of wastewater can be varied. Water is used in industry for a variety of purposes, often as a coolant or solvent. Industries like metal plating, tanning and brewing are all large sources of highly polluted wastewater. Some industries have high strength wastewaters that are high in organic pollutants or in dissolved metals. Most industrial facilities have their own unique treatment systems that cater to the unique properties of these facilities creating the wastewater.

Agricultural wastewater is produced from agricultural practices. Overwatering a field of vegetables can wash away fertilizers and pesticides that were applied to a field. Thus, the water can become contaminated with other substances. Another important source of agricultural wastewater is the run-off from poultry, fish and cattle farming. In all of these cases, water is used to clean the cages and wash away the feces of the animals. This wastewater is usually much stronger than domestic sources, and has the greatest possibility of finding its way into rivers and streams.

This module focuses on domestic wastewater treatment, although the others sources of wastewater should not be neglected when discussing wastewater. It is also important to understand that the same biological processes that we use on domestic wastewater can also be used to treat industrial and agricultural wastewater.

<u>Wastewater Constituents:</u>

Before we can understand wastewater's effects on natural systems and the ways to treat it, we need to understand what is in it. The majority of wastewater is simply water! Everything else is found in small amounts, yet they are in high enough concentrations that they drastically affect water quality.

Of great concern to human health, wastewater contains a number of microorganisms, the diversity of which can be impressive. Microbes found in wastewater come primarily from feces, but some microbes are also brought into the system when people take showers and wash their hands. Although not all of the microbes present in wastewater are **pathogens**, or disease causing organisms, many are. Some of the most

Figure E2: Second page of Teach Engineering document.

prevalent diseases worldwide are a result of inadequate sanitation. Due to their health risk, microbes need to be removed or destroyed in the wastewater treatment process.

Organic molecules, or molecules contain carbon and are biologically derived, are found in abundance in wastewater. Organic molecules come from human wastes as well as food wastes. These molecules are problematic as they contain large amounts of energy. Microbes view these molecules the same way we view candy bars. They can readily consume the molecules as a food source. This will be expounded upon later.

Nutrients are also readily found in wastewater. One way to think about nutrients is to think of them as dissolved fertilizers that plants can use to grow. In wastewater nitrogen and phosphorous are the two most important nutrients that people consider, as they are often the two nutrients of highest demand by plants.

Wastewater also contains a small amount of salts and metals. These tiny dissolved constituents are difficult to remove and are often found in very small concentrations. Our body gets rid of metals and nutrients on a regular basis through our urine. Once excreted by our body, these salts and metals find their way into wastewater. The concentrations of these are usually so low, that they are not removed before being returned to natural environments.

Lastly, and quite importantly wastewater contains trace amounts of pharmaceutical products. Every time we take medicines, a small percentage of it exits our system without being broken down. Anything from birth control to painkillers can end up passing through our body. Normally, what passes through our system is in very small concentrations. However, we are still not sure of the effect these compounds might have on wildlife, nor are we sure if our current treatment systems are effective at breaking these compounds down. This module focuses on the removal of organic molecules, microorganisms and nutrients found within wastewater.

<u>Wastewater's Impact on the Environment:</u>

Figure E1. Photo from India showing a river heavily contaminated by wastewaster

When raw wastewater enters a river or lake, it throws off the natural balance of that system. The introduction of large quantities of organic compounds as well as nutrients allows some organisms to grow

Figure E3: Third page of Teach Engineering document.

uncontrolled. It is similar to dumping tons of food on a very hungry community. The organisms that can use the organics and nutrients for growth start to thrive. Normally bacteria and algae are the only organisms that stand to benefit from the influx of wastewater. This explosion of microbial life is called **eutrophication**, depicted in figure 2. Most bacteria, just like us, require oxygen to consume organics. Thus, as they begin consuming what is in the wastewater they begin consuming all of the oxygen in the water. Larger organisms like fish and water insects, which are vital to natural ecosystems, require dissolved oxygen in the water to survive. As the oxygen is depleted, these higher order organisms begin to die off.

A similar problem is encountered when algae populations begin to explode due to the nutrients in wastewater. However, algae add oxygen to the water, at least at the beginning. What normally happens is that the algae population explodes to a point in which they consume all of the nutrients in the wastewater and begin to die off due to a lack of nutrients. As they begin to die, they become food to bacteria, which as stated before consume all the oxygen in the water. Both pathways lead to the eventual destruction of a habitat. That is why wastewater treatment focuses on the removal of the organics and nutrients from wastewater.

Figure E2. Eutrophic lake in Costa Rica. The bright green color is the lake is due to an abundance of algae growing in the lake.

Mimicking Nature:

How exactly do we remove the organics and nutrients from wastewater? The answer might be surprising! Why don't we mimic the same process that occurs in nature but in a controlled environment? We know that the microbes are breaking down the organic molecules and we know that other microbes can use the nutrients to grow, thereby removing the nutrients from the water. That is exactly what environmental engineers do to treat wastewater. Environmental engineers create the perfect environment for microbes to thrive and break down as many organics as possible.

Diversity of Microbial Life:

What about the really strong types of wastewater? What about the exotic compounds found in some high strength wastewaters? Of great benefit to humanity is the fact that there exists such a large variety of microbes on this planet. Each of which has found a **niche habitat**, or unique environment, in which to

Figure E4: Fourth page of Teach Engineering document.

dwell. These habitats can range from places of near zero pH to places with a pH of 10, environments that are normally colder than freezing to places like thermal vents that are near boiling temperature. In addition to being able to withstand these harsh environments, there is a diversity in compounds that microbes can degrade. There are organisms that can readily consume materials that would normally be toxic to most others. There are organisms that can consume radioactive material, others that use arsenic for their genetic material, and the list goes on. This diversity allows environmental engineers to select for the exact organisms that can withstand the conditions of a specific wastewater and be able to degrade the specific types of organics in the wastewater of interest.

Why are some organisms able to degrade compounds while other are not? Microbes are able to use organics because of specific **enzymes** that their genetics encode for. **Enzymes** are biologically derived **catalysts**. A catalyst is something that speeds up the rate of a reaction but is not consumed by the reaction. Microbes produce these enzymes to speed up the breakdown of specific organic molecules. Each enzyme is specific to one molecule. This concept isn't that foreign to everyday life. Our own bodies produce enzymes that allow us to consume the food we eat on a regular basis. Most people know someone that is lactose intolerant. If someone is lactose intolerant, it means their body does not produce the enzyme necessary to breakdown lactose, a sugar commonly found in dairy. In that same way, some microbes are able to generate enzymes that others are unable to produce.

Bioreactors:

So once we have selected for the right set of microbes, where do we grow them? What conditions affect microbial growth? Engineers and microbiologist grow microbes in devices they call **bioreactors**. Bioreactors are devices that encourage biological activity. You can think of it as a microbe's workplace. If you want to make the microbial community work harder and faster you need to make sure the conditions are just right. Things like pH, temperature and aeration are all important factors affecting microbial growth in a bioreactor. Most organisms like a neutral pH, slightly higher temperatures and considerable aeration, although these factors are greatly influenced by type of organism that has been selected.

Bioreactors are also used when a product that only microbes can make is desired. Alcohol fermentation, the process used to make beer and wine, occurs in a fermenter, which is just one type of bioreactor. Cheese and yogurt production also occurs in a type of bioreactor. These are familiar examples of bioreactors, but the most widely used example of a bioreactor is actually a wastewater treatment plant. A wastewater treatment plant tries to create the perfect conditions for microbes to remove the organics and the nutrients from wastewater.

The primary process of a wastewater treatment plant is the aeration basin. This large tank is aerated constantly in order to provide enough oxygen for the microbes to degrade the organics in wastewater. In this process, the microbes utilize large amounts of the nutrients for their own growth.

Working with Microbes- Measuring growth:

When working with microbes, it is important to understand which factors affect growth the most. One way to tell whether or not a microbe enjoys its bioreactor is to see how well it grows in the new environment. Measuring growth with microbes can be a difficult thing to do due to their size. To accurately measure growth, scientist use a variety of tools to determine cell growth, including direct cell counting and optical density.

Direct cell counting, sounds exactly like what it is. Scientists take samples of their reactors and look at them under a microscope. With specialized microscope slides (depicted in figure 3) scientist can see exactly how many microbes are in a specific volume. The samples are placed on a tiny grid on the slide. Each box on the grid corresponds to a specific volume of sample. Then, just like counting sheep, the engineer can count all of the microbes per grid. This gives them a cell count that is in cells per volume. This is one of the most common methods for measuring and determining cellular growth and activity.

Figure E5: Fifth page of Teach Engineering document.

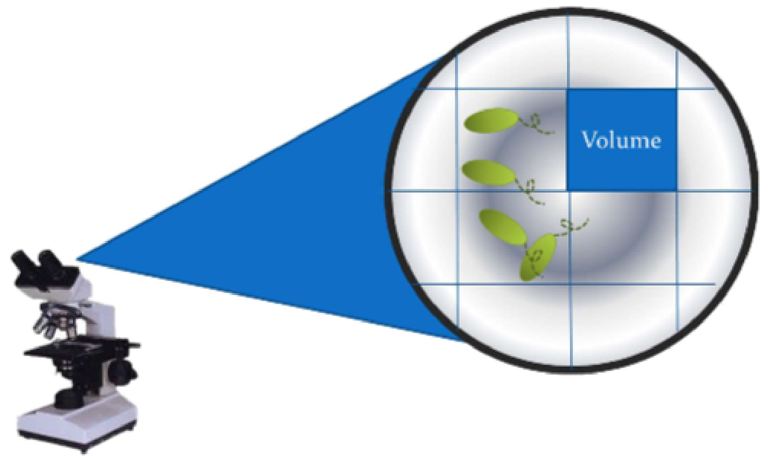

Figure E3. Depiction of direct cell counting, showing the microscope and what a scientist would see if a sample were placed on a slide.

Although direct cell counting can be a useful method of determining growth, there are easier, more generalized methods. **Optical density** is a method that uses light to measure growth. Cells absorb light. The more cells you have a container the more they are going to absorb the light that passes through it. Engineers have taken this natural phenomenon and used it to their advantage. Using optical density as a tool, engineers pass light through a container of microbes and measure how much light passes through the container. This process is depicted in figure 5. Each time an engineer uses this tool, he compares the new value against clean water (his blank). If you were to monitor microbial growth over time and graph it you would end up with a **growth curve**.

A growth curve is a graph that depicts all the life stages experienced by a bacterial community. A generic curve is depicted in figure 6. When microbes are put in a new environment free of competition and abounding in food, they normally go through four stages of growth: The lag phase, exponential growth phase, stationary phase and death phase. In lag phase, the microbes are just warming up the new environment. They haven't started reproducing very quickly yet. What they are really doing is getting used to the new food source. During exponential growth phase, the microbe population explodes and starts growing uncontrollably. Here they are growing exponentially. In the stationary phase, their growth starts to slow down and they reach a point where the amount of microbes being born is equal to the amount of microbes dying.

Figure E6: Sixth page of Teach Engineering document.

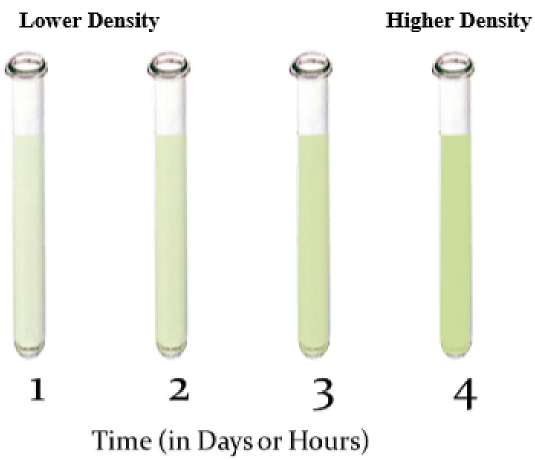

Figure E4. Cell growth in test tube over time. As the cells grow, the test tube becomes more opaque and less light is able to pass through.

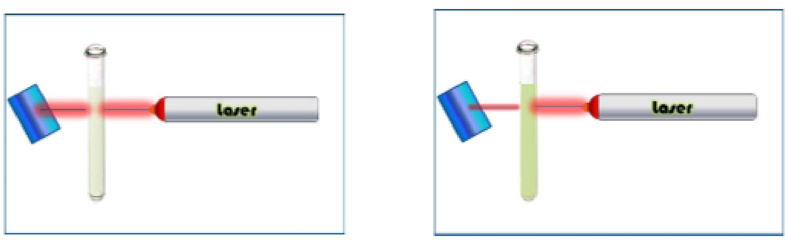

Figure E5. Cell growth can be measured by passing a light though the test tubes containing the microbes. A device that reads the amount of light that passes through can be used to indicate the amount of growth over time.

Microbes enter into stationary phase for a variety of reasons, all of which are related to something changing in their environment. Usually the food source in their environment starts to be depleted, thus the environment can't sustain an endless number of microbes. Another common reason for the microbes to die off is that as they grow they produce waste products. These waste products can often be toxic to the microorganisms and end up killing them. The last stage, the death phase, occurs when the conditions in the

Figure E7: Seventh page of Teach Engineering document.

microbe's environment have changed so drastically that bulk of the population starts to die off.

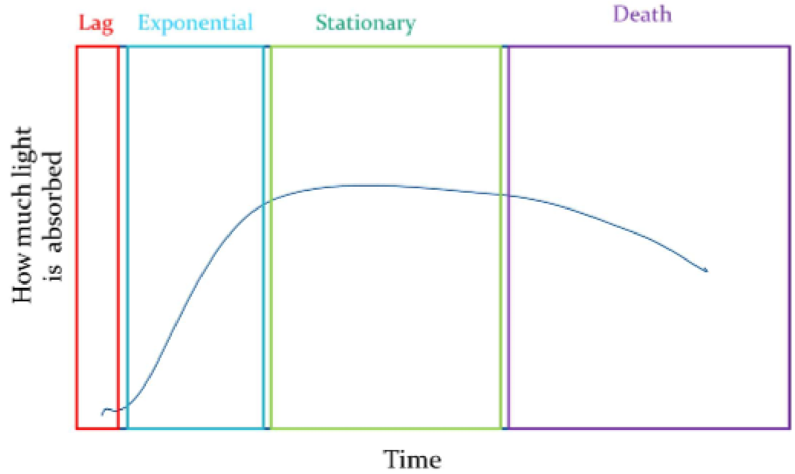

Figure E6. Illustration of a generalized microbial growth curve.

Engineers use direct cell counting and optical density to determine how a microbe's growth rate changes according to different environmental conditions. The goal is to keep the microbes healthy and happy and doing important tasks. With the example of wastewater, it is important to keep the microbes growing in the exponential phase.

Conclusion:

Engineers use microbes on a daily basis to clean the water that we have polluted. When carefully monitored microbes can accomplish a variety of other services and even produce valuable products. We are entering a new era where bioengineering, or putting microbes to work, can help us solve many of the problems that have faced humanity for centuries.

Figure E8: Eighth page of Teach Engineering document.

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Journal Title: Water Science and Technology

Paper Reference Number: WST - EM15531R1

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

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Robert Bair is a doctoral candidate in the Department of Civil and Environmental Engineering and a member of the Membrane Biotechnology Lab Group at the University of South Florida. Mr. Bair's research focuses on anaerobic membrane bioreactors for domestic wastewater treatment in urban areas of developing countries. As a recipient of USF Graduate School's Challenge Grant, he has experience with the design, construction and operation of small-scale anaerobic digesters for food waste treatment, as well as anaerobic membrane bioreactors. His aim is to make cutting-edge sanitation technologies relevant and applicable to the world's urban poor through innovative design.