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Jorge Luis Calabria
University of South Florida, Jlcalabr@mail.usf.edu

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Wastewater Nutrient Recovery Using Anaerobic Membrane Bioreactor (AnMBR) Permeate for Hydroponic Fertigation

by

Jorge L. Calabria

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Environmental Engineering
Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

Major Professor: Daniel H. Yeh, Ph.D.
Albert Robert Rubin, Ph.D.
Piet Lens, Ph.D.

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DEDICATION

To my family for their constant support and encouragement to always achieve more

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ABSTRACT

The imbalance between global population growth and resource consumption is indicative of unsustainable practices and foreshadows a grim future of continued resource depletion, food and water scarcity, social inequality, and deteriorating public and environmental health. Meanwhile, the urban centers of the world continue to experience exponential growth resulting in overwhelmed food, water, and sanitation infrastructure. Decentralized and satellite wastewater treatment technologies capable of resource recovery, such as anaerobic membrane bioreactors (AnMBR), foster synergistic opportunities to help manage the food, energy, and water sectors of urban environments. Specifically, the nutrient concentration and high effluent quality of permeate produced by AnMBR systems present applicability in controlled environment agriculture (CEA). The efficacy of AnMBR permeate is evaluated in a hydroponics growth study of cucumber (*Cucumis sativus*) grown in an outdoor greenhouse and tomato (*Lycopersicon lycopersicum)* grown indoors. Nutrient analysis of permeate generated by a small, pilot scale AnMBR developed for the treatment of domestic wastewater at ambient temperature indicated sufficient concentrations of N and P elements, however high proportion of NH_4^+ in N species decreased growth performance. Opportunities for optimizing AnMBR permeate for hydroponics applications exist and thus imply synergistic integration of decentralized AnMBR technology with controlled environment agriculture (CEA) such as hydroponics. A model is proposed for the integration of decentralized AnMBR and CEA systems capable of producing usable plant products within the urban environment. The integration of these systems is proposed as a solution to the challenges of with food security, stressed water supplies, and environmental degradation associated with unchecked urban growth in the developing and developed world.

CHAPTER 1: INTRODUCTION

The recovery of resources from wastes is the paradigm that will shape the perspectives of future generations as they approach the problems associated with increasing global population and decreasing finite resources. The continued use of finite resources to sustain human practices has been recognized as unsustainable and the consequences of such overly consumptive behavior are being realized in the form of fresh water shortages, vast deforestation, and vast social inequality.

In the midst of the vast consumption of non-renewable resources, there is a stockpile of seemingly untapped resources that will continue to grow along with the global population: waste. The growth of developing nations, especially China and India, will continue to increase the rates at which non-renewable resources are consumed and wastes are generated. It is a moral and social imperative to not only strive to reduce the amount of waste generated, but also to pursue any and all utilization potential from waste before it is finally discarded. Wastewater in particular, is a by-product of society that possesses potential for resource recovery. What other renewable resource has the capacity to grow in supply along with the growth of the population? Some of the resources contained within wastewater include nutrients, energy, and water. The recovery of these resources from wastewater could serve to assist in the sustainable management of those resources which will be essential in sustaining continued growth worldwide.

Advancements in waste treatment technology are fostering economically feasible methods for recovering resources from waste streams. Anaerobic membrane bioreactor (AnMBR) technology has performed well in laboratory settings to treat high strength wastewater. In addition to treatment performance, AnMBR technology can easily be designed to recover resources such as nutrients, energy, and water. The sanitation and resource recovery capabilities of AnMBRs prove favorable in many regions of the world that lack access to sanitation due to lack of infrastructure, distance from centralized treatment, low –income areas. Additionally, recovered resources can be utilized on site introducing new economic opportunities in the area surrounding the point of generation. Nutrients contained in the filtered effluent, or permeate, that is produced by AnMBRs could serve as fertilizer for agricultural operations to produce commercially valuable crops. Agricultural operations fueled by resources recovered from wastewater holds implications of improving food security in low income areas and ensuring more sustainable management of the food and water sectors. The majority of the world is experiencing rapid urbanization. The sustainable management of food and water couldn't be more important in such high density areas. The work conducted in this thesis serves to explore the performance of permeate generated by an AnMBR when applied as a hydroponic nutrient solution. Acceptable performance would ensure adequate plant growth while minimizing the risk of pathogens and malnutrition. Additionally, this work will present a model for integrating an AnMBR treatment process with a small scale hydroponics operation based off the system by which the research was made possible.

The ability to support plant growth in hydroponics systems with AnMBR permeate would create opportunities for integrating wastewater treatment and agricultural production while decreasing the footprint of both operations. Such integration could solve many problems associated with high density urban areas. The implications of utilizing AnMBR permeate for agriculture highlight sustainable practices for providing the most basic of human needs. The future of wastewater treatment will operate under the paradigm of utilizing waste as a resource. The materials in wastewater will be recycled and reused, ultimately lowering the impact of human practices on the environment and securing a sustainable future.

1.1 Background

1.1.1 Urbanization and the Need for Sustainable Food and Water Management

The population of the global community continues to experience exponential growth in the number of human beings on the earth and also in the amount of resources consumed to sustain our growth. Moreover, not only are populations growing, but countries such as China and India are experiencing a rise in their middle class. This rise to affluence will only be experienced by more and more areas of the world as technology continues to enhance the ability to access information. However, this growth has been facilitated by the unsustainable consumption of resources (e.g. fossil fuels, fresh water, phosphorous). Additionally, the increase of human activity has served to be synonymous with increases in carbon emissions contributing to global climate change and thus intensifying the effects of resource shortages.

The effects of declining resource availability and quality are harshest in the dense, urban areas of developing countries which lack adequate infrastructure for the provision of basic needs. Urban areas are experiencing growth rates three times that of rural areas in some areas (Cofie, O.O., Dreschel, P.P., Agbottah, S.S., & Van Veenhuizen, R., 2009). For the first time more than half of the world's population was living in cities in 2007. As is the case in many developing countries, urbanization harbors urban poverty, increased pollution, increased unemployment and increases in food insecurity and malnutrition, especially in children and pregnant and lactating women. It is projected that this rate of global urbanization will continue to increase, yielding the birth of several megalopolises (over 10,000,000 inhabitants) across the world (Orsini, F., Kahane, R., Nono-Womdim, R., & Gianguinto, G., 2013). The consequences of such growth impact urban planning, public health, and food and water supplies especially (Orsini, F. et al., 2013).

Urban poverty has also been on the rise as urbanization increases, especially in the cities of developing countries. The world's poor that once dwelled predominantly in rural areas, in the modern world are settling into cities. Roughly 12.6% of the world's population (32.7% of global urban population) lives in areas classified by the United Nations as slums. Across the world, the number of people living in slums totals about 1 billion out of which 220 million are in Africa, 598 million in Asia, and 134 million in Latin America (Orsini, F. et al., 2013). In addition, more than half of the urban population lives below the poverty line. Those living in poverty are the most vulnerable to instability in food and water supplies as well as high unemployment. While high quality food may be available in some areas, it may not always be affordable. As a result, actual diets consumed consist of food that is of lower quality and quantity, leading to inadequate nutrition (FAO,IFAD & WFP, 2013). Hunger and malnutrition adversely affect the well-being of the urban poor across the world; this pattern is seen even in developed countries such as the United States where millions of urban poor cannot afford nutritious food necessary for proper health. Additionally, urban settings commonly contain both rich and poor populations which cause a divide in the equitable access to food, thus further destabilizing food security (Gupta, R. & Gangopadhyay, S.G., 2013). There is ample justification for concern regarding food security. It is thus imperative that food production, distribution, consumption, and the associated wastes generated be managed in a sustainable manner so as to fulfill current needs and to ensure that future generations may be able to meet their needs.

Yet another consequence of increased urbanization is the growing demand for fresh water and the growing amount of wastes that are discharge into the environment causing further pollution of clean water sources. Within the next 50 years, it is estimated that more than 40% of the World’s population will live in countries experiencing water stress and water scarcity (Maheshwari, B., Purohit, R., Malano, H., Singh, V.P., & Amerasinghe, P., 2014). Wastewater however, can serve to mitigate the issue of water scarcity through the utilization of resource recovery practices. Farmers worldwide have long been aware of the value of wastewater and the resources associated with its use in agricultural applications. In many areas wastewater is available, yielding a year round source of water and nutrient resources with potential for agricultural applications. In areas where water is scarcely used for the conveyance of waste materials, improved sanitation technology is necessary for capturing and extracting resource materials. Implementing resource recovery strategies could serve to improve the overall sustainability of urban agricultural practices as well as alleviate environmental impacts and problems stemming from water scarcity ("WHO Guidelines for theSafe Use of Wastewater, Excreta and Greywater," 2006).

1.1.2 Engineering Grand Challenge: Manage the Nitrogen Cycle

The production of ammonia for fertilizer applications via the Haber-Bosch process[1] is estimated to be responsible for causing the population boom in the early 1900's and for sustaining over a third of the world's population. These effects were a result of the increase in food production caused by the industrial method for nitrogen fertilizer production. It is estimated that the number of humans supported per hectare of arable land has increased from 1.9 to 4.3 persons between 1908 (the time of the invention of the Haber process) and 2008 (Erisman, J.W., Sutton, M.A., Galloway, J., Winiwarter, W., & Klimont, Z., 2008). Although the widespread use of nitrogen fertilizer has benefited and sustained population growth, excess nitrogen that releases into the environment is known to cause many human and environmental side effects such as drinking water contamination, algal blooms, loss of biodiversity, and even contributing to climate change (Erisman, J.W. et al., 2008).

In 2005, approximately 100 Tg of nitrogen (N) was produced by the Haber-Bosch process for use in global agriculture, however roughly 17 Tg of N in the form of crops, dairy, and meat was consumed by humans (Erisman, J.W. et al., 2008). This represents a staggeringly low nitrogen use efficiency (mass N retrieved per unit nitrogen applied). Approximately 40% of applied nitrogen fertilizer is lost due to denitrification into the form of unreactive atmospheric nitrogen, representing a waste of 32 MJ kg^{-1} N fixed by the Haber-Bosch process or 1% of the global primary energy supply (Erisman, J.W. et al., 2008). Problems occur when the unaccounted for reactive nitrogen is released and accumulated in environmental reservoirs causing consortia of environmental damage including: production of tropospheric ozone and aerosols, manipulation of terrestrial fauna growth cycles leading to a loss of biodiversity, acidification of lakes and streams, eutrophication, hypoxia, and forms oxidized nitrogen compounds that are an extremely

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[1] A process invented by German chemist Fritz Haber for the synthesis of ammonia from its elements and was later developed for an industrial scale by Carl Bosch.

potent greenhouse gas (Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B., & Cosby, B.J., 2003).

In 2008, the U.S. National Academy of Engineering (NAE) declared the need for management of the nitrogen cycle as one of the Grand Challenges for Engineering ("Grand Challenges for Engineering," 2008). In his analysis, Galloway et al. (2003) outlines possibilities for intervention of the nitrogen cycle by decreasing the amount of reactive nitrogen entering environmental reservoirs. In regards to food production, this means a drastic increase in nitrogen use efficiency is essential. Hydroponics systems have the ability to improve nitrogen-use efficiency (NUE) because these systems can operate in controlled environments where nutrients such as reactive nitrogen can be recirculated until converted to plant biomass. "Precise farming" techniques such as these have been tested extensively with promising results regarding nutrient and water use efficiency. The environmental impacts associated with the use of nitrogen fertilizer span all global change issues. It is imperative to improve nitrogen use efficiency in order to minimize these effects. Closely monitored and controlled agriculture practices present a hopeful opportunity to improve nitrogen use efficiency and thus, improve management of the nitrogen cycle.

1.1.3 The Role of Decentralized Wastewater Treatment

The need for sustainable management of resources such as water, nutrients and energy is further exacerbated by population growth, urbanization, and climate change. These factors are stressing water supplies and the chances of tapping new water supplies for expanding metropolitan areas will become increasingly difficult, if not impossible (Guest, J.S., Skerlos, S.J., Barnard, J.L., Beck, M.B., Daigger, G.T., Hilger, H., Jackson, S.J., Karvazy, K., Kelly, L., Macpherson, L., Mihelcic, J.R., Pramanik, A., Raskin, L., Van Loosdrecht, M.C.M., Yeh, D., & Love, N.G., 2009; Tchobanoglous, G., Stensel, H.D., Tsuchihashi, R., Burton, F., Abu-Orf, M., Bowden, G., & Pfrang, W., 2014). From a fundamental sustainability standpoint, it is necessary to acknowledge wastewater as a renewable resource from which water, energy and materials -such as nutrients and bioplastics- can be recovered(Guest, J.S. et al., 2009). Tchobanoglous et al. (2014) argues that one way in order to accommodate the increasing stress and demands on water resources is to enable existing water supplies to reach farther. Water reuse represents the practice necessary to achieve this.

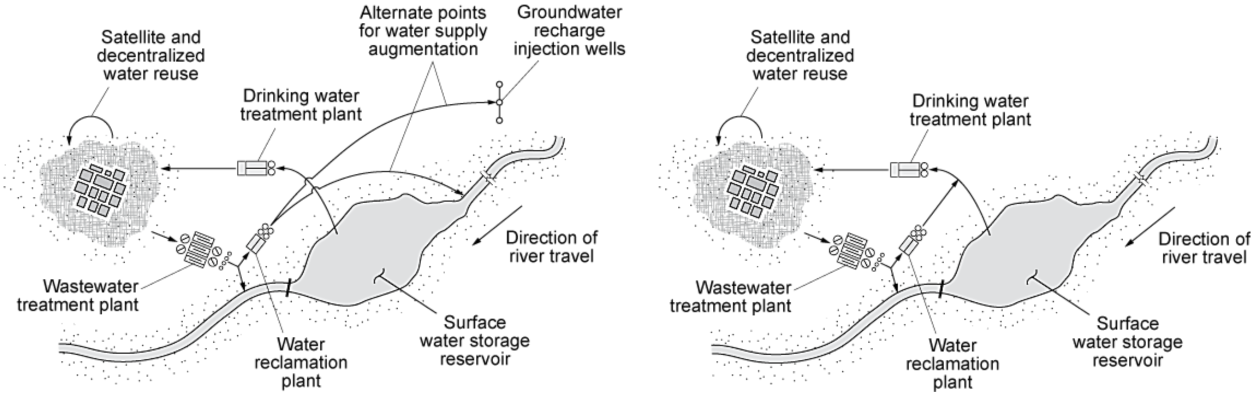

Figure 1 Direct and indirect potable reuse (Reused with permission from Tchobanoglous, G., Wastewater Treatment Trends in the 21st Century, 2013)

Tchobanoglous et al. (2014) describes supplementing municipal water supplies by means of indirect potable reuse or direct potable reuse (IPR or DPR)(Gikas, P. & Tchobanoglous, G., 2009; Tchobanoglous, G. et al., 2014). Historically, treatment systems have operated with the focus of *removing* contaminants and then discharging the acceptable effluent back into the environment representing a resource intensive, linear process of water management. Advancements in wastewater treatment technology and unit processes have been able to improve the effluent quality and resource recovery capabilities of existing treatment facilities, however these capabilities were introduced as complimentary unit processes as opposed to integrated in the original design and construction of infrastructure. In order to obtain the highest levels of performance and reliability, Tchobanoglous et al. (2014) speculates that water and wastewater systems of future advanced infrastructures will likely include decentralization, remote management, resource recovery source separation of waste streams, and application of specific optimization of water quality (Tchobanoglous, G. et al., 2014). Furthermore, as urbanization continues to increase, centralized treatment systems will continue to experience performance declines and failures as they reach and exceed their capacities. Yet another disadvantage of centralized infrastructure is the potential for widespread impacts related to process failures due to natural disasters. The public health impacts associated with centralized system failures are far greater than those of decentralized systems(Gikas, P. & Tchobanoglous, G., 2009).

The opportunities for recovering resources from wastewater become more feasible when treatment systems and infrastructures allow for wastewater treatment and reuse at or near the point of generation.

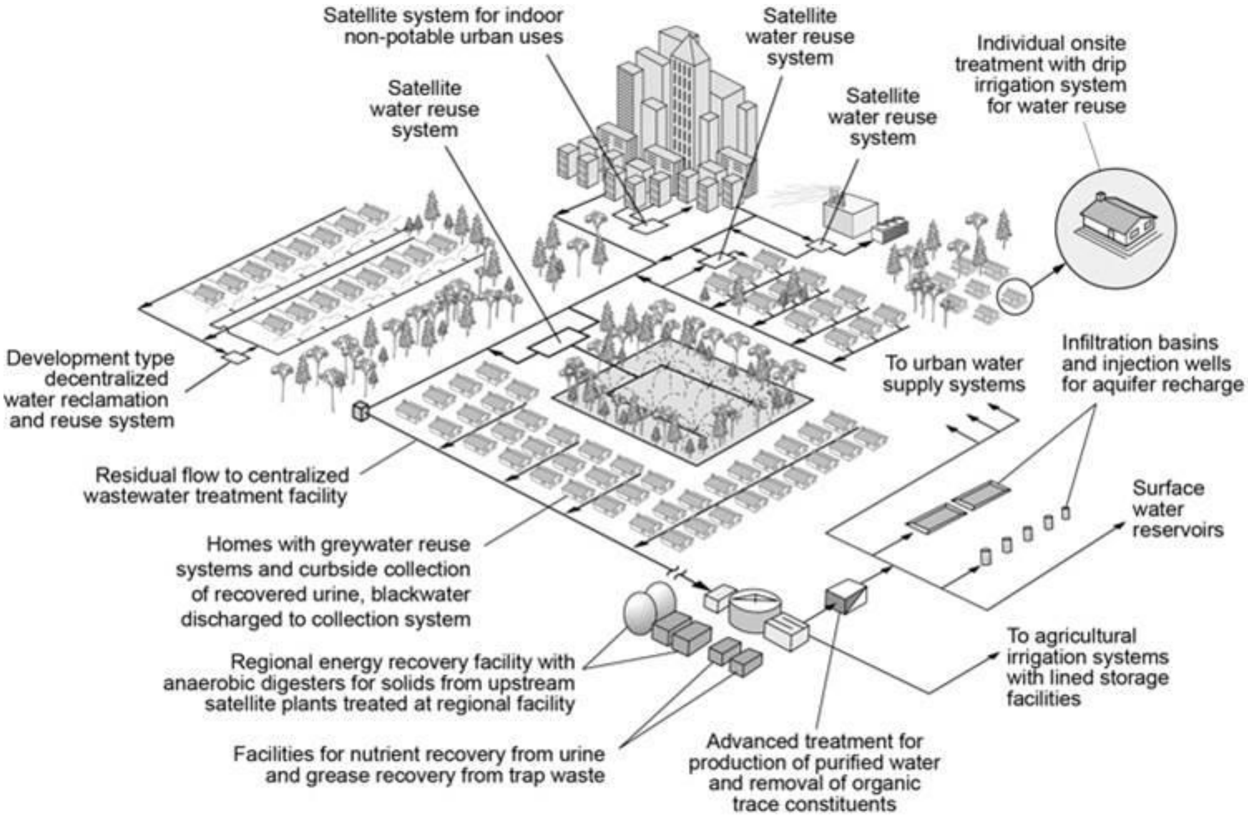

Figure 2 Example of integrated wastewater management using decentralized, satellite, and centralized facilities (Reused with permission from Tchobanoglous, G., Wastewater Treatment Trends in the 21st Century, 2013)

Figure 2 illustrates applications of various satellite and decentralized reclamation facilities, thus proposing a model for the sustainable management of water and wastewater systems. Satellite and decentralized systems can vary according to their application. Satellite wastewater treatment systems usually lack solids processing facilities and serve to maximize water reuse while minimizing wastewater flows.

Interception systems intercept wastewater before reaching the collection system which is then diverted to a satellite system for treatment and local reuse purposes including toilet flushing, landscaping, and cooling water in commercial and/or residential buildings. Extraction type systems “mine” wastewater

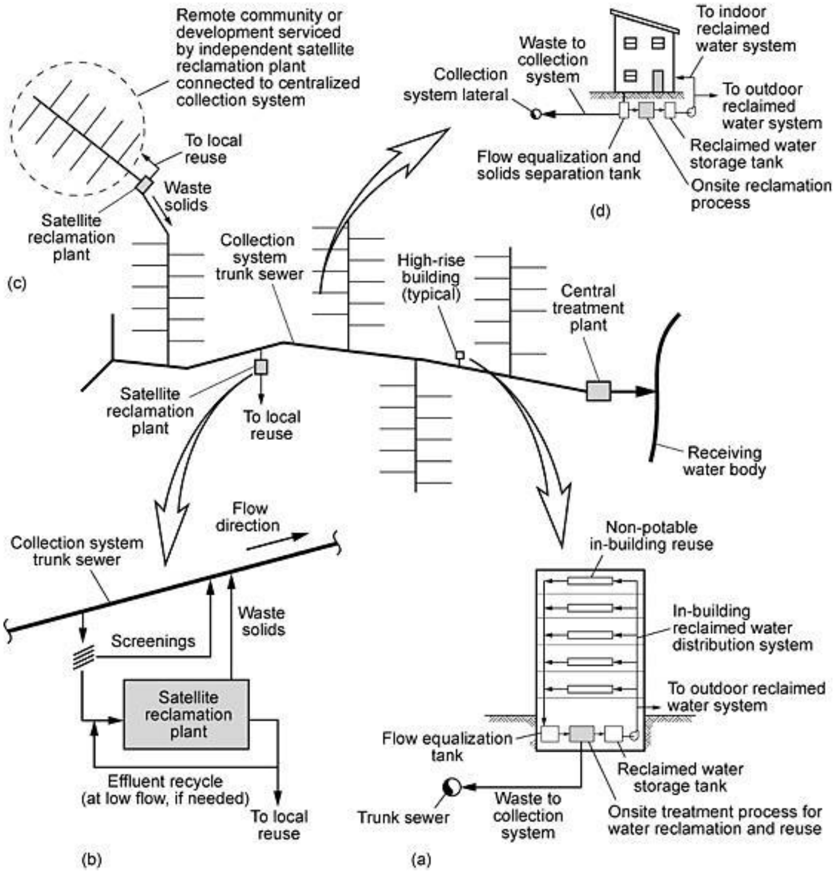

Figure 3 Strategic implementation of decentralized and satellite treatment systems (Reused with permission from Tchobanoglous, G., Wastewater Treatment Trends in the 21st Century, 2013)

from the collection system while in route to the central treatment facility to further increase the use of wastewater resources. Finally, upstream systems treat waters upstream of centralized systems to satisfy any localized demands for reclaimed water, but can also be used for IPR through groundwater recharge and surface water irrigation (Gikas, P. & Tchobanoglous, G., 2009). Figure 5 illustrates examples of how decentralized treatment systems can be integrated with central treatment systems in the urban and suburban environment.

Decentralized systems that utilize AnMBR technology hold advantages of solids treatment capabilities, small operating footprint, and high quality effluent producing capabilities (Stephenson, T., Judd, S., Jefferson, B., & Brindle, K., 2000). Such systems could serve a single household in a rural setting to a cluster of houses to even an entire subdivision. Decentralized treatment systems can even be applied on the scale of larger campuses such as universities or industrial, commercial, and agricultural facilities. Effluent produced from decentralized systems utilizing technologies such as AnMBRs can serve a variety of local applications: irrigation for landscaping, substitute or replace non-potable water uses (toilet flushing), and for use as cooling water (Gikas, P. & Tchobanoglous, G., 2009). Resource recovery measures such as these will help to alleviate the continued stressing of water supplies caused by increasing urbanization.

Decentralized treatment systems can play an even more vital role in high-density urban settings of developing areas around the world. These areas are subject to having a large portion of their populations living in informal housing settlements, or slums. Countries like Rwanda, Uganda, Nigeria, and Bangladesh are experiencing situations where more than 50% of the urban population dwells in slums (*The Millenium Development Goals Report*, 2013). Due to high population density, slums experience high rates of transmission of waterborne diseases facilitated by the lack of adequate water and sanitation infrastructure (Holden, R., 2008). Decentralized technologies that are commonly employed in these areas such as pit latrines, composting toilets, leach pits, and septic tanks often are overwhelmed by the unique challenges posed by slum areas. Challenges such as high use frequencies, unreliable or non-existent water and power infrastructure due to lack of government support yield a harsh environment for sanitation efforts. Proper implementation of robust decentralized treatment systems capable of resource recovery would not only benefit public health in these areas by improving sanitation, but can potentially improve quality of life by providing resources of value.

1.1.4 Urban Agriculture for the Enhancement of Food Security

In addition to its effect on water supplies, rapid urbanization has led to the transformation of agricultural lands surrounding cities to non-agricultural use, thus impacting the food production sector. The poorly planned conversion of these peri-urban landscapes has led to increased runoff, decreases in fertile land, declining biodiversity, and degradation of water quality. While simultaneously, the increasing food, water, and energy demands of cities are further disrupting the balance of resource production and consumption, ultimately foreshadowing declining livability in cities (Maheshwari, B. et al., 2014). In most developing countries, the rapid rate of urbanization is outpacing the growth of services and employment. The lack of holistic planning for infrastructures to support urbanization has left cities - especially those of developing countries- ill equipped to handle the challenges associated with increasing populations and decreasing resource reservoirs. According to Maheshwari et al., (2014) the future success and sustainability of urban centers relies on the ability to face a number of critical challenges (Maheshwari, B. et al., 2014). These abilities include:

- Supply potable water and remove and treat the resulting wastewater stream
- Adapt to the increasing threat of climate change and the need to reduce, energy and greenhouse gas (GHG) emissions.
- Mitigate the urban heat island phenomenon which traps atmospheric pollutants and deteriorates quality of life in urban centers (Vasilakopoulou, K.,Kolokotsa, D. & Santamouris, M., 2014)
- Provide sustainable infrastructure and minimize risks to food security, and
- Maintain biodiversity.

Urban agriculture (UA) is experiencing a strong resurgence due to the increasing demand for urban food security (Veenhuizen, R., 2006). The success of UA practices across the world have caught the attention of governments and authorities which are becoming more and more supportive, foreshadowing better management and promotion of urban food production. The spatial implication of urban agriculture practices is the deciding factor which dictates the extent or scale to which urban agriculture practices are implemented.

Food security, as defined by the Food and Agricultural Organization of the United Nations (FAO), is the situation that “exists when all people, at all times, have physical, social and economic access to sufficient, safe, and nutritious food which meets their dietary needs and food preferences for an active and healthy life” (FAO et al., 2013). The benefits to the management of water supplies associated with decentralized treatment and resource recovery mirror the possible benefits to the urban food sector. As mentioned before, decentralized treatment systems capable of resource recovery can extract water and nutrients contained in wastewater. Water and nutrients are necessary for agricultural operations, however in urban settings, land space most certainly is at a premium, and thus conventional methods of in-soil food production may not be feasible. Hydroponics systems eliminate the need for arable land for crop production and foster increase yields per unit area making hydroponic cultivation methods ideal for cramped urban environments (Resh, H.M., 2001). Furthermore, integrating food production operations with decentralized wastewater treatment plants can create urban oases that provide the dual function of eliminating waste while providing food, ultimately enhancing public health through improved sanitation and food security.

1.2 Objectives

This work will serve to analyze the performance of AnMBR permeate when utilized as a nutrient fertilizer solution for agricultural applications. A model demonstrating the integration of small scale horticultural operations with decentralized wastewater treatment is proposed for enhancing sanitation and food security in urban settings.

1.3 Scope of Work

- Measures the growth performances of plants grown in a hydroponics system using AnMBR permeate as the nutritional source.
- Analyze deficiencies in AnMBR permeate nutrient content through interpretation of plant stress observations and growth measurements.
- Propose a model for a system that integrates decentralized wastewater treatment with hydroponics for urban agriculture applications
- Demonstrate the economic feasibility of the proposed system using cost/benefit analyses.

CHAPTER 2: LITERATURE REVIEW

2.1 Anaerobic Membrane Bioreactor (AnMBR)

The anaerobic membrane bioreactor (AnMBR) is defined simply as the combination of membrane filtration with an anaerobic bioreactor (Liao, B.-Q. & Bagley, D.M., 2006). 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[2], 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, S.,Alspach, B. & Vickers, J., 2005; Crittenden, J. & Harza, M.W., 2005). Within the wastewater treatment sector, membrane bioreactors (MBRs) have a number of advantages over conventional activated sludge (CAS) processes. MBRs are able to increase the cell concentrations within bioreactors[3] which results in increased in microbial activity (Drews, A. & Kraume, M., 2005). By increasing microbial activity, the reactor size can be minimized while still achieving high treatment efficiency. Thus, MBR technology is suitable for areas where small footprint is required (e.g. decentralized treatment plants in dense urban settings). Complete retention of biomass within the reactor also indicates 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, M.-L., Aguinaldo, J., Arabi, S., Sadler, M.E., Min, K., Liu, M., Salamon, C., Greiner, A.D., Diamond, J., McCandless, R., Owerdierck, C., Wert, J., & Padhye, L.P., 2013). MBR operation can also be automated to a greater extent than conventional

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[2] Reverse osmosis and nanofiltration membranes are much tighter membranes which require higher pressures for operation. They are typically used for desalination, water softening and for ultra-pure water applications.

[3] A bioreactor is a vessel in which microbes are grown and used to mediate chemical processes.

treatment systems allowing for more decentralized treatment (DiGiano, F.A., Andreottola, G., Adham, S., Buckley, C., Cornel, P., Daigger, G., Fane, A., Galil, N., Jacangelo, J., & Pollice, A., 2004; Kraemer, J.T., Menniti, A.L., Erdal, Z.K., Constantine, T.A., Johnson, B.R., Daigger, G.T., & Crawford, G.V., 2012). MBRs for wastewater treatment have been in existence since the 1970s, however large-scale implementation didn't start until the 1990s (Kraemer, J.T. et al., 2012; Yang, W.,Cicek, N. & Ilg, J., 2006). 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, F.A. et al., 2004; Kraemer, J.T. et al., 2012).

2.1.1 Overview of the Anaerobic Process for Wastewater Treatment

The biological processes of anaerobic fermentation and oxidation (also known as anaerobic digestion, or AD) facilitate the degradation of organic materials in anaerobic reactor. The consortia of anaerobic organisms responsible for anaerobic fermentation and oxidation grow slowly due to the low energy availability for biological synthesis. Thus these microorganisms prefer long solids retention times (SRT) and a low hydraulic retention times (HRT) in order to achieve the breakdown of waste streams rich in complex, carbon molecules. Table 1 describes the advantages and disadvantages of anaerobic processes. The successful treatment performance of AnMBR systems is attributed to their configuration which allows for the successful decoupling SRT and HRT, usually achieved through biofilm or granule formation (Visvanathan, C. & Abeynayaka, A., 2011).

The anaerobic oxidation of waste material contains three basic steps: (1) hydrolysis, (2) acidogenesis (also known as fermentation), and (3) methanogenesis. Figure 4 provides a schematic illustration of the overall process of anaerobic oxidation, expressing the fate of various solid materials (Tchobanoglous, G. et al., 2014). An intermediate step, known as acetogenesis, takes place to convert some of the VFAs produced during acidogenesis to acetic acid.

Table 1 Advantages and disadvantages of anaerobic processes compared to aerobic processes (adapted from Tchobanoglous, et al., 2014)

Advantages	**Disadvantages**
Less energy required	Longer startup time need to grow biomass
Less biological sludge production	May require addition of alkalinity
Less nutrients required	Not capable of biological N & P removal
Methane production (source of energy)	Much more susceptible to temperature drop effects of reaction rates
Ability to quickly respond to substrate addition after long periods of starvation	May be more susceptible to upsets due to toxic substances or extreme changes in feed
Elimination of off gas air pollution	May require further treatment to meet discharge requirements
Smaller reactor volume	Potential of odor production and corrosiveness of gas
Effective pretreatment process	
Potential for lower carbon footprint	

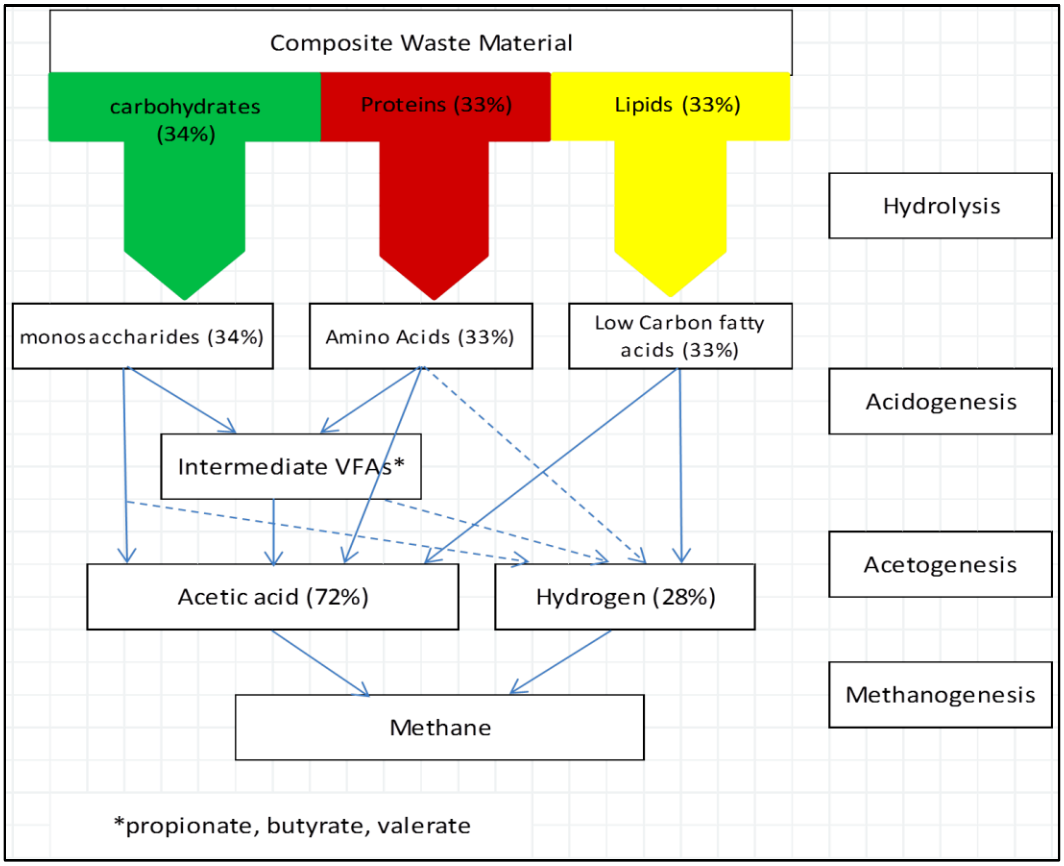

Figure 4 Schematic of overall anaerobic digestion process (adapted from Tchobanoglous, et al., 2014)

Hydrolysis involves the conversion or particulate matter into soluble compounds that can readily degrade further to simple monomers which are utilized by bacteria for fermentation. This process is facilitated by extracellular enzymes from various anaerobic organisms. Materials that are comprised of dense or woody plant material, such as paper, lawn and yard clippings often experience a long hydrolysis phase as the lignocellulosic content of these materials is difficult to degrade (Rittman, B.E. & McCarty, P., 2001; Tchobanoglous, G. et al., 2014). High strength wastewater such as those produced from sugar processing facilities contain high concentrations of soluble organic material that can seemingly skip the hydrolysis step and be ready for *fermentation.*

The second step of AD, known as *acidogenesis* or *fermentation*, involves the biological conversion of soluble substrate material into volatile fatty acids, CO_2, and hydrogen as shown in Figure 4**.** Acids produced during acidogenesis are fermented further to form acetate, and more CO_2 and hydrogen. The acids (propionic acid, butyric acid, and valeric acid) formed during *acidogenesis* are fermented further to form acetate during *acetogenesis.* The amount of acids, hydrogen, and CO_2 produced in these processes can lower the pH of a reactor should sufficient levels of alkalinity not be present. Sufficient alkalinity is important to buffer the pH drop associated with these steps so as to not inhibit methanogenic activity which is particularly sensitive to low pH (Rittman, B.E. & McCarty, P., 2001; Tchobanoglous, G. et al., 2014).

The last basic step, *methanogenesis*, is performed by the group of *Archaea organisms* recognized as methanogens. As their name suggests, these organisms generate methane by two methods: *aceticlastic methanogenesis* and *hydrogenotrophic methanogenesis*. *Aceticlastic methanogenesis*, responsible for 72% of the methane performed in AD, is carried out by "splitting" acetate into methane and CO_2. *Hydrogenotrophic methanogens* utilize hydrogen as an electron donor and CO_2 as an electron acceptor to produce methane. These methanogenic pathways are represented by the stoichiometric reactions below (Tchobanoglous, G. et al., 2014).

Hydrogenotrophic methanogenesis: $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

Aceticlastic methanogenesis: $CH_3COOH \rightarrow CH_4 + CO_2$

Methane produced during the AD of waste is a valuable by-product and represents one method for recovering energy from waste. Historically, anaerobic digestion processes have been utilized by wastewater treatment facilities for processing waste activated sludge and solids collected during primary treatment(Tchobanoglous, G. et al., 2014). The biogas that is generated during the anaerobic digestion of sludges is 60 to 65 percent methane and approximately 30 percent carbon dioxide. Biogas production is desirable because it produces a useable fuel in the form of methane that can be used to offset power consumption. One can estimate the anticipated methane production produced during AD by performing a COD balance to account for the changes in COD during fermentation and oxidation. During AD, COD is converted to CH_4. The COD of methane is the amount of oxygen required to oxidize methane to the carbon dioxide and water. The following stoichiometric equation is used to determine the COD of methane (Rittman, B.E. & McCarty, P., 2001; Tchobanoglous, G. et al., 2014):

$$CH_4 + 2O_2 \rightarrow CO_2 + H_2O$$

The COD of one mole of methane is 2*(32g O_2/mole) = 64 g O_2/mole CH_4. The volume of methane at standard conditions (0°C and 1 atm) is 22.414 liters. Under anaerobic conditions, the theoretical volume of CH_4 produced per gram of COD entering the system is 22.414 L/64 g COD = 0.35 L CH_4/g COD at standard conditions (Rittman, B.E. & McCarty, P., 2001). Various factors affect biological performance in an anaerobic system, influencing the rate and amount of COD that is oxidized CH_4.

Anaerobic treatment is capable of treating wastes containing high concentrations of oxygen demanding substances commonly referred to as chemical oxygen demand (COD). COD represents the variety of substances that consume oxygen molecules when degraded. COD is defined as the oxygen equivalent of the organic material in wastewater that can be oxidized chemically using dichromate in an acid solution(Sawyer, C.N.,McCarty, P.L. & Parkin, G.F., 2003). High COD concentration in wastewater is of concern as it can cause environmental degradation by consuming the dissolved oxygen in receiving waters resulting in loss of aquatic life and a condition known as eutrophication.

A major advantage of AnMBR technology is its ability to accept high loading rates while maintaining treatment performance. A study conducted by Harada et al., (1994) using synthetic wastewater at a concentration of 5000 mg l^{-1} with a loading rate of 1 kg COD $m^{-3}d^{-1}$ observed significant increases in the protein and sugar levels in the biomass, yet permeate COD concentrations remained stable at a level below 80 mg l^{-1}. Removal efficiencies of >90% have been reported at loading rates of 15 kg COD m^{-3} d^{-1} for various types of wastewaters treated with AnMBRs (Kayawake, E.,Narukami, Y. & Yamagata, M., 1991; Li, A.,Kothari, D. & Corrado, J.J., 1985; Strohwald, N.K.H. & Ross, W.R., 1992).

Table 2 Dry weight quantity of waste discharged per capita in the United States

Value, lbs./capita*day				**Value, g/capita*day**		
Constituent	**Range**	**Typical w/o ground up kitchen waste**	**Typical w/ground up kitchen waste**	**Range**	**Typical w/o ground up kitchen waste**	**Typical w/ground up kitchen waste**
BOD	0.11-0.26	0.15	0.2	50-120	68.0	90.7
COD	0.30-0.65	0.4	0.5	110-295	181.4	226.8
TSS	0.13-0.33	0.15	0.19	60-150	68.0	86.2
NH3 as N	0.011-0.026	0.017	0.017	5-12	7.7	7.7
Organic N as N	0.009-0.022	0.012	0.013	4-10	5.4	5.9
TKN as N	0.02-0.04	0.029	0.031	9-18	13.2	14.1
Organic P as P	0.002-0.004	0.0026	0.0029	0.9-1.8	1.2	1.3
Inorganic P as P	0.001-0.006	0.002	0.002	0.50-2.7	0.9	0.9
Total P as P	0.009-0.015	0.0046	0.0048	1.5-4.5	2.1	2.2
Potassium, K	0.022-0.077	0.013	0.014	4-7	5.9	6.4
Oil and Grease	0.022-0.077	0.062	0.07	10-35	28.1	31.8

Feedstock composition is important to assess as the concentration of nutrients within the feedstock for an anaerobic system directly affects the COD removal efficiency. As with all biological treatment systems, there must be sufficient concentrations of key nutrients to accommodate the growth requirements of the organisms involved. The composition of domestic wastewater (see Table 2 above) generally contains all nutrients required to sustain the growth of anaerobic microorganisms. Table 3 shows the nutrient requirements for anaerobic treatment processes and in addition, provides the recommended background concentrations of nutrients to ensure treatment performance.

Table 3 Nutrient requirements for anaerobic digestion (adapted from Speece, 1996)

Element		**Requirement mg/g COD**	**Desired excess Conc. (mg/l)**
Macronutrients	Nitrogen	5 - 15	50
	Phosphorus	0.8 - 2.5	10
	Sulfur	1 - 3	5
Micronutrients	Iron	0.03	10
	Cobalt	0.003	0.02
	Nickel	0.004	0.02
	Zinc	0.02	0.02
	Copper	0.004	0.02
	Manganese	0.004	0.02
	Molybdenum	0.004	0.05
	Selenium	0.004	0.08
	Tungsten	0.004	0.02
	Boron	0.004	0.02
Common Cations	Sodium	-	100-200
	Potassium	-	200-400
	Calcium	-	100-200
	Magnesium	-	75-250

Anaerobic systems also require trace metals for the activation of enzymes that are essential to methanogenesis. Lack of sufficient trace nutrients such as iron, cobalt, and nickel can yield anaerobic treatment failure; iron needs to be in concentrations as high as 40 ppm for optimal process performance (Speece, R.E., 1996). A disadvantage of anaerobic treatment systems is the toxicity conditions that can be caused by a wide variety of materials, thus warranting the careful observation of feed material so as not to cause a system failure. Inhibitory substances include: heavy metals, light metals, chlorinated hydrocarbons, cyanides, and high concentrations of ammonia, sulfide, and even VFAs. Reduction of biogas production and accumulation of organic acids such as propionic acid are textbook indicators of anaerobic process inhibition (McCarty, P.L.,Bae, J. & Kim, J., 2011; Visvanathan, C. & Abeynayaka, A., 2011).

Various factors affect toxicity conditions. Temperature and pH for example, can alter the form of ammonia. A higher pH would yield a higher proportion of ammonia in the unionized form of NH_3 which presents toxicity conditions in anaerobic environments when concentrations reach around 100 mg/l. Contrarily, inhibition wasn't experienced by the NH_4^+ form of ammonia until concentrations reached about 3000 mg/l (Rittman, B.E. & McCarty, P., 2001).

Anaerobic processes are sensitive to temperature, pH, inhibitory substances, and nutrient limitations. Neutral pH is preferred in anaerobic systems as a pH of 6.8 or lower results in inhibition of anaerobic activity. Fluctuations in reactor temperature should not exceed 0.6 to 1.2 °C per day (WPCF, 1987). Anaerobic processes produce large quantities of CO_2 gas warranting the need for sufficient alkalinity to maintain pH neutrality. Alkalinity concentrations often used are in the range of 3000 to 5000 mg/l as $CaCO_3$ (Tchobanoglous, G. et al., 2014). During the digestion of sludge, alkalinity is produced from the degradation of amino acids to produce ammonia (NH_3) which combines with CO_2 and H_2O to form alkalinity in the form of NH_4 (HCO_3). It is necessary to add additional alkalinity when system feed material contains high amounts of carbohydrates which tend to contribute more CO_2 (Rittman, B.E. & McCarty, P., 2001).

Temperature directly affects the rate at which microorganisms involved in methanogenesis grow as well as the rate of reactions that facilitate methanogenesis. The slow growth that is characteristic of methanogenic organisms can be enhanced by increasing the temperature. Growth rates generally double for every 10°C increase in temperature. The operating temperature range for mesophilic methanogens is between 10-35°C, thus rate growth rates cease to increase at temperatures between 35-40°C (Rittman, B.E. & McCarty, P., 2001). Highly concentrated wastewater streams or those of high enough temperature to sustain thermophilic experience rates that are 50 to 100% higher than at the optimum mesophilic temperature, thus, decrease the volume need by the system to achieve the same treatment capacity (Rittman, B.E. & McCarty, P., 2001). However, the advantages of thermophilic (shown in Table 4 below) operation has many disadvantages as well that require consideration in the design of anaerobic process.

Table 4 Advantages and disadvantages of thermophilic AD compared to mesophilic AD (adapted from (Tchobanoglous, G. et al., 2014)

Advantages	**Disadvantages**
1. Improved Pathogen Destruction, potential for Class A sludge production	1. Non-batch processes require EPA certification for Class A Approval
2. Reaction rate is increased, reducing volume requirements	2.Increased requirement for thermal energy
3. May increase overall volatile solids reduction	3.Biosolids may present dewatering problems
4. Same components and design as mesophilic digester	4.Higher odor potential in dewatered cake
	5. Increased ammonia content in dewatering side stream
	6. Process may lack stability
	7. Increased system complexity requiring heat recovery
	8. May be more susceptible to foaming

2.1.2 Membrane Bioreactor (MBR) Process

The key elements of any membrane process are influenced by the following parameters on the overall permeate flux (Judd, S. & Jefferson, B., 2003).

- Membrane resistance
- Operational driving force per unit membrane area
- Hydrodynamic conditions at membrane-liquid interface
- Fouling and subsequent cleaning of membrane surface

Flux is the term used to describe the amount of material of material that passes through a unit area of membrane material per unit time. Flux is sometimes referred to as the permeate velocity and is reported in SI units as $m^3\ m^{-2}\ s^{-1}$, or $m\ s^{-1}$, or more commonly as $l\ m^{-2}\ h^{-1}$ (LMH). General operational fluxes are between 10 and 1000 LMH (Judd, S. & Jefferson, B., 2003).

There are three streams involved in membrane processes: the feed, concentrate, and permeate. The concentrate, or retentate, consists of unpermeated product. Dead-end operation (Figure 5) lacks a concentrate stream and is restricted to waters with relatively low solids content. For applications with waters that contain high solids concentrations and/or dense membranes with limited flux, cross-flow filtration (Figure 6) is employed. Cross-flow operation has the added benefit of scouring the membrane-solution interface with retentate solids which discourages the buildup of solids on the membrane surface (Judd, S. & Jefferson, B., 2003).

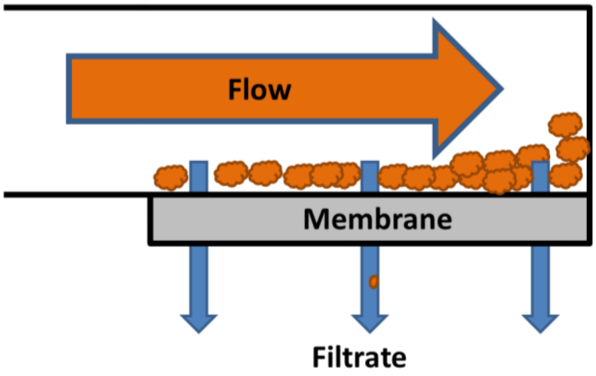

Figure 5 Dead-end filtration

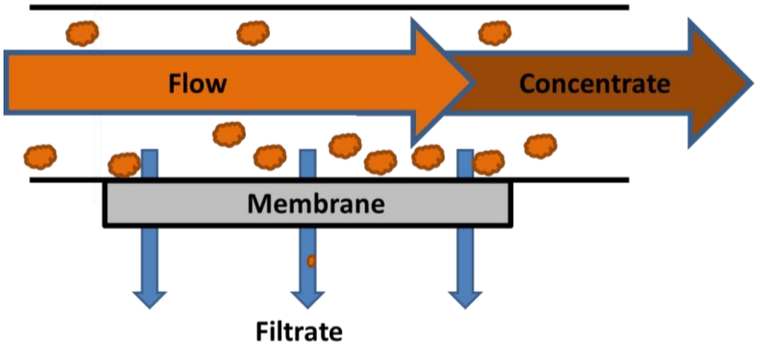

Figure 6 Cross-flow filtration

Total membrane area combined with the membrane flux determines the conversion or recovery of the membrane process. Conversion is expressed as the percentage of the amount of feed recovered as permeate, represented as Θ. For a feed concentration C and flow Q, mass balance dictates that:

$$Q = Q_P + Q_R$$

$$QC = Q_P C_P + Q_R C_R$$

Conversion is given by:

$$\Theta = Q_P/Q$$

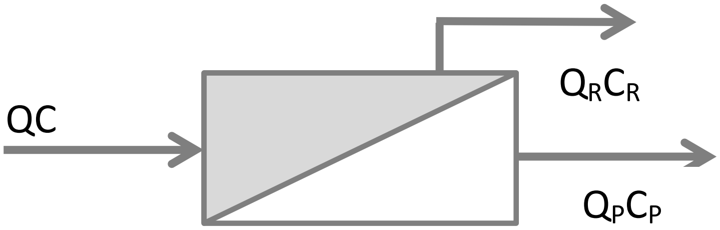

Figure 7 The mass balance for a membrane module

The driving force for processes involving membrane filtration and reverse osmosis is normally a gradient of transmembrane pressure (TMP). TMP can be influenced by the accumulation of biological and/or precipitated solids on the membrane surface, more commonly known as fouling. Various biological and physiochemical mechanisms contribute to fouling. Fouling is different from clogging, where clogging is associated with inadequate hydrodynamic performance (Judd, S. & Jefferson, B., 2003).

Fouling is one of the major disadvantages associated with the operation of MBRs due to the negative effects fouling has on membrane performance (Van Lier, J.B. & Lettinga, G., 1999). Both membrane flux and permeate water quality declines with increased fouling. Thus, fouling can increase operating costs of an MBR system. Factors that influence fouling can vary: membrane properties such as membrane pore size, surface characteristics, characteristics of solvents and solutes in the feed, and the hydrodynamic profile of the MBR.

Major foulants include colloidal particles, organic macromolecules, inorganics such as metal hydroxides and calcium, and particulates. Changes in pH and localized concentration (saturation) can cause precipitation of salts and hydroxides, a phenomenon commonly referred to as concentration polarization. Pore size influences fouling mechanisms. Larger pore size in membrane can lead to internal fouling within the pores while membranes with smaller pore sizes can experience a buildup of a “cake” biofilm layer. At times this biofilm layer can prove advantages by providing additional filtration (Judd, S. & Jefferson, B., 2003).

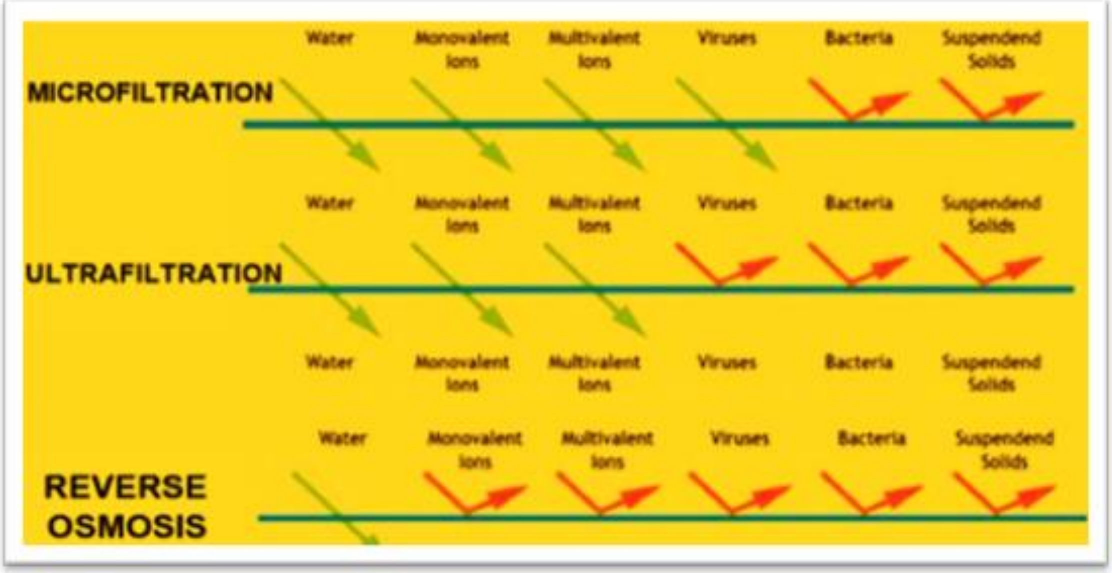

Figure 8 Illustration of the types of membranes and the materials they reject (from public domain by UNSW3004SepG23 (Own work) [CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons).

Fouling prevention begins with identification and characterization of fouling. Changes in system operation (intermittent flow, change in SRT) often effect fouling. Smith (2011) found that fouling can be mitigated through membrane design, biological process design, and through efficient air scouring concepts/designs.

Backwashing and cleaning are processes employed by operators for the removal of foulants from membranes. Backwashing involves the intermittent reversal of water flow through the membrane while cleaning involves chemical treatment for an extended period of time. While backflushing and chemical cleaning are employed to safeguard the performance of MBR systems, these processes incur costs associated with energy consumption for pumping, system downtime, loss of product water, and the use of chemical cleaning agents (Judd, S. & Jefferson, B., 2003). Smith et al. (2013) identifies the need for inexpensive fouling reduction and control that is necessary for full scale implementation of AnMBR technology.

2.1.3 AnMBR Operation Considerations

The slow growth rates and sensitivity of microbial populations of anaerobic processes yield complex scenarios necessary for adequate operation. Anaerobic process performance is enhanced when the biomass of a reactor is retained. The coupling of ultrafiltration with anaerobic processes presents opportunities for treating high-strength wastewaters that require long SRT in order to achieve adequate COD removal. In addition to COD removal, a major indicator that motivates optimal system performance is methane production. A great amount of research has been conducted and is still underway to determine how to produce the greatest quantity of methane possible (Visvanathan, C. & Abeynayaka, A., 2011).

The membrane portion of AnMBR systems can be operated under pressure or by vacuum. Pressurized membrane operation consists of an external membrane module that uses a pump to push permeate through the membrane; this configuration is also known as external cross-flow. This configuration utilizes the liquid cross-flow velocity to discourage cake formation on the membrane.

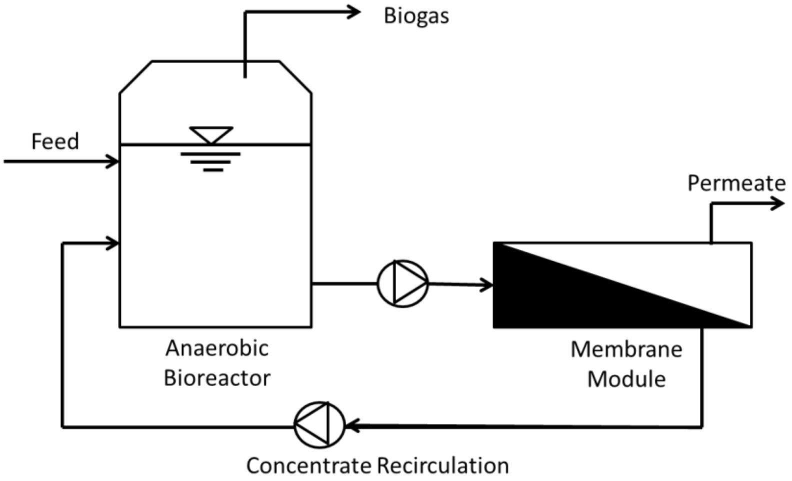

Figure 9 Single-stage AnMBR in external cross-flow configuration (adapted from (Visvanathan, C. & Abeynayaka, A., 2011)

Hydraulic head or a pump is used to force liquid through the membrane. The characteristics of closed, anaerobic systems deem submerged membrane configurations non-ideal from an operation and maintenance perspective. A study conducted by Wijekoon et al. (2011) investigated the effect of intermittent dead-end mode operation for reduced pump costs and better sludge performance from biomass activity reduction (Visvanathan, C. & Abeynayaka, A., 2011; Wijekoon, K.C.,Visvanathan, C. & Abeynayaka, A., 2011).

Another reactor configuration is the two stage reactor which separates the fermentative processes and the methanogenic processes into two reactors (Figure 10 below). The first reactor houses the processes of hydrolyses, acidogenesis, and acetogenesis while the second reactor carries out methanogenesis. This configuration allows for the highly sensitive methanogenic microorganisms to perform methanogenesis in an optimal and stable pH range. This poses advantages over single stage reactor configurations which can be conducive to a microbial environment where different species are in direct competition with each other, ultimately resulting in a decline of system performance. Separating the fermentative stages from the methanogenesis stage ensures that methanogenic organisms will not be inhibited by the accumulation of fermentation products such as volatile fatty acids. Temperature can also be phased to in the two stage configuration to assist the rate of reactions in each stage. Increasing temperature during hydrolysis for example has been shown to improve the rate at which complex materials are degraded (Liao, B.-Q. & Bagley, D.M., 2006; McCarty, P.L. et al., 2011; Tchobanoglous, G. et al., 2014; Visvanathan, C. & Abeynayaka, A., 2011).

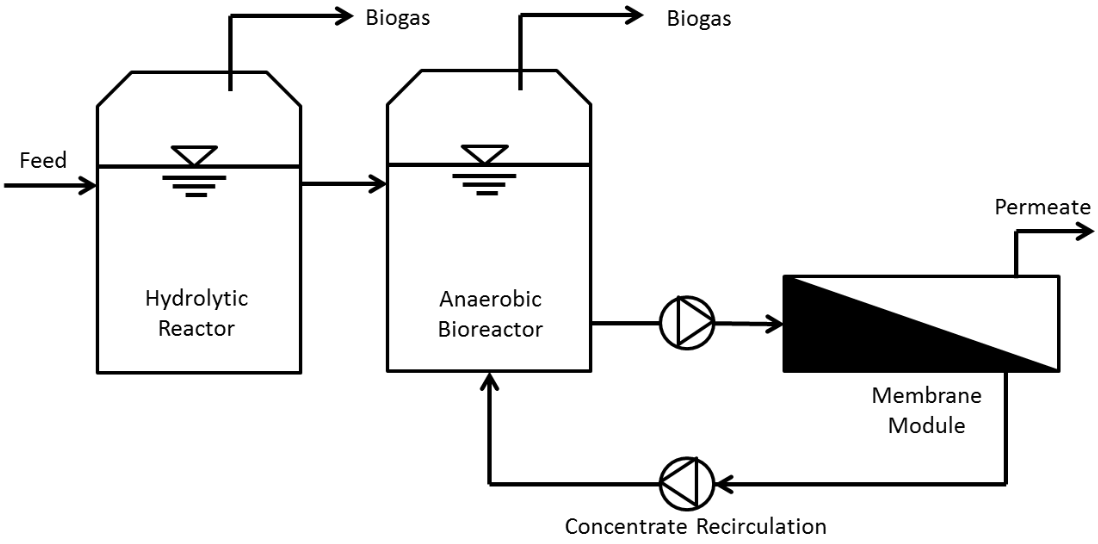

Figure 10 Two-stage AnMBR configuration (adapted from (Visvanathan, C. & Abeynayaka, A., 2011)

AnMBR system operation is flexible in that a wide range of operation characteristics can be tolerated in regards to feed concentration, loading rate, reactor type, and temperature. Regardless of membrane configuration, the anaerobic bioreactor is most commonly operated as a continuously stirred tank reactor (CSTR) (Smith, Adam L, Stadler, Lauren B, Love, Nancy G, Skerlos, Steven J, & Raskin, Lutgarde, 2012). Other reactors have been proposed that retain biomass within the bioreactor, reducing the amount of biomass that comes in contact with an external membrane module, ultimately reducing fouling (Kim, J., Kim, K., Ye, H., Lee, E., Shin, C., McCarty, P.L., & Bae, J., 2010; Liao, B.-Q. & Bagley, D.M., 2006). Studies have researched the effect of cross-flow velocity on biomass activity reduction, suggesting that CFV should not exceed 5 m/s in order to minimize biomass activity reduction (Visvanathan, C. & Abeynayaka, A., 2011). The mechanical sheer stress that is applied to the biomass as a result of pumping promotes size reduction of the biomass flocs which, in turn, promotes fouling (Visvanathan, C. & Abeynayaka, A., 2011).

Successful AnMBR systems have indicated desired operational fluxes to be in the range of 5–20 LMH (Liao, B.-Q. & Bagley, D.M., 2006; Wang, Z., Ye, S., Wu, Z., & Tang, S., 2010). This operational flux is still low compared to that of aerobic MBRs, thus improvements must be made to overcome membrane fouling (Visvanathan, C. & Abeynayaka, A., 2011). Dynamic membranes (DM) have been applied in aerobic MBR systems to reduce fouling. In a study, Zhang et al. (2010) achieved a high permeate flux of 65 LMH with a DM formed by suspended solids in the settling zone and soluble microbial byproducts (SMP) and extra-polymeric substances (EPS) (Zhang, X., Wang, Z., Wu, Z., Lu, F., Tong, J., & Zang, L., 2010).

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, P.L. et al., 2011). A study using an AnMBR for domestic wastewater treatment used just one-tenth of the energy that a typical aerobic MBR would use (Kim, J. et al., 2010). The system effluent, or permeate, usually contains soluble nutrients like nitrogen and phosphorous which can be used to fertilize plants or algae near the point of generation (McCarty, P.L. et al., 2011). It is this attribute of the AnMBR technology that motivated this study. The ability to produce liquid effluent of high nutrient content that is free of pathogens is what makes AnMBR technologies appropriate for agricultural applications (Jensen, M.H. & Collins, W.L., 1985).

2.2 Controlled Environment Agriculture (CEA)

Controlled-environment agriculture (CEA) involves all aspects of modifying the natural environment to achieve plant and animal growth. In the case of plants, CEA involves the modification of conditions in both root and aerial zones. Because atmospheric control is a major objective, most CEA operations take place inside enclosures that accommodate control over air temperature, lighting, moisture, and climatic protection (Jensen, M.H. & Collins, W.L., 1985). In soil agriculture remains the dominant agricultural practice throughout the world; however advancements in environmental monitoring and control technologies have promoted interest in controlled-environment agriculture. Additionally, as urbanization continues, land space will become a high commodity driving the need for land efficient agriculture. Complexity is also increased significantly in CEA systems warranting highly knowledgeable operating staff to maintain system performance. A deep understanding of the nutritional and environmental requirements of plants being grown is crucial to the success of any CEA operation. As research continues to explore the performance of plants in these systems, automation technology will soon be able to reduce the complexity associated with operation of these systems.

2.2.1 Plant Nutrition

When considering the state of technology today and the quality of life that advancements in technology have provided, it compares little to the benefits provided by chlorophyll-containing plants. Without plants, our planet would be a grim and desolate place. When chlorophyll is exposed to sunlight (wavelengths between 400-700 nm visible light), photon energy is converted to chemical energy (plant carbohydrates) in the process known as photosynthesis. In this process, water molecules are split and the hydrogen protons produced are combined with carbon dioxide to form a carbohydrate molecule and oxygen is released. The process is depicted in the equation below(Jones, J.B., 1998):

$$6CO_2 + 6\ H_2O + (\text{photon energy} + \text{chlorophyll}) \rightarrow C_6H_{12}O_6 + 6O_2$$

Plants provide a plethora of benefits that serve to sustain the natural and human environments including:

- Maintaining atmospheric balance of oxygen and carbon dioxide
- Providing atmospheric moisture through transpiration
- Controlling soil erosion
- Recycling soil nutrients
- Providing food and fiber materials

Of the myriads of plant species, a small portion is grown for human consumption and use. Grain crops such as wheat, rice and corn fulfill the carbohydrate requirements of the human diet while fruit and vegetable plants serve as major sources of protein and vitamins(Jones, J.B., 1998). Plants have adapted to varying environments across the globe and thus are far ranging in their individual requirements for growth including: temperature, moisture tolerance, light conditions, and nutrient element requirements. Most plants have either a wide or narrow range of adaptability to changes in the environmental conditions. The nutritional requirements share equal variability and are parameters that have been the subject of countless studies to enhance the yield and quality of plant production. Additionally, a number of pant species have been modified genetically for improved performance. Scientists are even employing the beneficial properties of plants for space exploration as a means for removing carbon dioxide, supplying oxygen, and *recycling water and human wastes*¸ as well food production(Jones, J.B., 1998; Ming, D.W., Gruener, J.E., Henderson, K.E., Steinberg, S.L., Barta, D.J., & Galindo Jr., C., 2001). These activities represent controlled plant growth. Specific elements are essential for the normal growth and development of plants; these elements are commonly termed nutrients. The study of the need and effect of nutrients on the growth and development of plants is termed plant nutrition.

Scientists began to discover the elements essential for plant growth in the 1800s. History has witnessed countless theories regarding what is necessary for plant growth but only through close observation and carefully crafted experiments could scientist begin concluding requirements for plant growth. By the beginning of the 1900s, 10 of the 16 essential elements (now-known) had been identified. Early scientists had also concluded that live plants were comprised mainly of water and organic matter while mineral matter, in most plants, constituted 10% of the dry mass and frequently less than 5% of the dry mass (Hoagland, D.R. & Arnon, D.I., 1950; Jones, J.B., 1998).

In 1939, two plant physiologists established criteria for determining plant nutrient essentiality (Arnon, A.I. & Stout, P.R., 1939):

- Omission of the element in question must result in abnormal growth, failure to complete the life cycle, or premature death of the plant
- The element must be specific and not replaceable for another
- The element must exert its effect directly on growth or metabolism and not some indirect effect such as by antagonizing another element present at a toxic level

These criteria still serve as the governing criteria for determining essentiality of elements for plants. The last essential element to be discovered was chlorine over 40 years ago and to this day, plant physiologists are still actively engaged in determining what additional elements, if any, are essential for plant nutrition.

Table 5 The essential elements, their form for uptake, and functions in the plant (adapted from Mengel, 1987)

Essential element	**Form of uptake**	**Functions in plant**
C, H, O, N, S	Ions in solution (HCO_3^-, NO_3^-, NH_4^+, SO_4^{2-}) or gases in the atmosphere (O_2, N_2, SO_2)	Major constituents of organic substances
P, B	Ions in solution (PO_3^{3-}, BO_3^{3-})	Energy transfer reactions and carbohydrate movement
K, Mg, Ca, Cl	Ions in solution (K^+, Mg^{2+}, Ca^{2+}, Cl^-)	Non-specific functions, or specific components of organic compounds, or maintaining ionic balance
Cu, Fe, Mn, Mo, Zn	Ions or chelates in solution (Cu^{2+}, Fe^{2+}, Mn^{2+}, MoO^-, Zn^{2+}	Enable electron transport and catalysts for enzymes

In addition to elements designated as essential, a number of elements have been identified as beneficial to plant growth (see Table 3) for their ability to yield a beneficial effect on plant growth by (1) having a direct effect that relates specifically to that element and/or by (2) yielding enhanced growth by substitution for an essential element. Silicon for example, has been known to enhance the growth and appearance of rice by preventing plant lodging, thus indicating a requirement of sufficient silicon concentrations for the successful culture of rice (Jones, J.B., 1998).

Table 6 Trace element content of "Reference Plant". (No data from typical accumulator and/or rejecter plants) from (Markert, 1994)

Trace Element	**mg/kg**	**Trace Element**	**mg/kg**
Antimony (Sb)	0.1	Iodine (I)	3
Arsenic (As)	0.1	Lead (Pb)	1
Barium (Ba)	40	Mercury (Hg)	0.1
Beryllium (Be)	0.001	Nickel (Ni)	1.5
Bismuth (Bi)	0.01	Selenium (Se)	0.02
Bromine (Br)	4	Silver (Ag)	0.2
Cadmium (Cd)	0.05	Strontium (Sr)	50
Cerium (Ce)	0.5	Thallium (Tl)	0.05
Cesium (Cs)	0.2	Tin (Sn)	0.2
Chromium (Cr)	1.5	Titanium (Ti)	5
Fluorine (F)	2	Tungsten (W)	0.2
Gallium (Ga)	0.1	Uranium (U)	0.01
Gold (Au)	0.001	Vanadium	0.5

With the exception of C, H, and O, the remaining essential elements are primarily taken up through the roots of a plant as ions that exist in the root zone. Another exception is N, which in leguminous plants, can be provided to the plant by means of symbiotic-N_2 fixation. In soil culture, elements exist in either organic or inorganic substances or both. The decay of plant matter and microorganisms releases ions containing essential elements into the soil solution. The soil system represents an ever changing complex of dynamic chemical and biological systems that are affected by factors such as temperature, pH, moisture content, concentrations of various elements (essential, beneficial, or toxic) and amount of soil aeration(Jones, J.B., 1998; Mengel, S.W., 1987). Elements are taken up by roots once a certain proximity to the root is reached. Three processes describe the form by which ions are mobilized in the soil solution: mass flow, diffusion, and root interception.

As water moves in the soil, dissolved ions are transported with the moving water through the soil medium; this process is described as mass flow. The Ca and NO_3^- ions are mobilized in the soil primarily by mass flow. The bulk movement of ions from an area of high concentration to an area of low concentration is known the process of diffusion. Most ions of the essential elements move by diffusion in the soil medium. The uptake of ions by roots within the soil medium results in a concentration gradient that transports ions from high concentrations in the surrounding soil to the area of lowered concentration near the roots. As plant growth continues, the root system expands, increasing contact with soil medium particles by the process of root interception. The root itself will change anatomically, affecting the rate of ion uptake of the overall plant exponentially. The pH of the rhizosphere (the root-soil interface) will be more than one unit of pH less than that of the surrounding as a result of H ion released during root respiration (Jones, J.B., 1998). Root health is essential to overall plant health. Poor plant development can occur in soils of good overall health due to root damaging conditions such as:

- Root impairment by physical circumstance (soil compaction, anaerobic conditions, mechanical root pruning, etc.)
- Low soil temperature
- Low moisture which impairs mass flow and diffusion
- Excessive water which can yield anaerobic conditions
- Adverse biological activity stemming from disease and nematode infestation

Ions and water absorbed by the root move upward through the plant xylem. The driving force that moves water, ions and other dissolved solutes can be the transpiration of water from leaves that draws water up from the root zone, pressurization water by roots, and the source-sink phenomenon which draws water, ions, and solutes from inactive to active expanding portions (new growth, fruit, grain) of the plant.

Solute and ion movement is unidirectional in the xylem, driven predominantly by transpiration, while in the phloem, ion and solute movement is bi directional and movement is facilitated by the source-sink phenomenon. Additionally, cross transfer can occur from the xylem into the phloem, but not vice versa. Transport rates have been reported to be 10 to 100 cm/h in the xylem; transport in the phloem is considerably less.

The uptake, accumulation, and redistribution of elements by plants vary throughout the life of the plant. Young plants will exhibit rapid nutrient uptake until they reach maturity, where uptake and accumulation begin to decline. During the reproductive (fruit, flower, seed development) phase, elements are redistributed. The rate and extent of redistribution varies depending on the element. The known mobility characteristics of elements can help identify in what portion of the plant one would expect deficiency symptoms to occur. Deficiencies of elements of the most mobile elements occur in older leaves while deficiency of least mobile elements will occur in newly emerging and young leaves.

Visual symptoms may or may not occur when a plant is experiencing nutrient element insufficiency (deficiency or toxicity) occurs, although normal plant development will be hindered. When visual symptoms do occur, their distinct and accurate description can help to identify most nutritional disorders. Terminology that is used for describing visual symptoms on plants is given in Table 7. Elements that exist in excessive concentrations can cause deficiencies of other elements resulting in visual symptoms that can be identified with toxicities of other elements.

A number of elements, when present at the root level at elevated concentrations can be toxic to plants. For example, most of the micronutrients (B, Cl, Cu, Mn, and Zn) can yield toxicity effects if available in high concentrations to plants(Jones, J.B., 1998). Toxicity effects can be classified as *direct*, i.e. the element itself directly impacts the plant, or as *indirect* by reducing the availability of another element or by interfering with normal physiological processes within the plant. Plants can also exhibit no signs of nutrient element insufficiency and exhibit seemingly normal development. This condition, known as *hidden hunger*, is a concern for grow operations as the plant will not show insufficiency until final yields and crop quality are assessed. Hidden hunger that goes unchecked can lead to crops of lesser quality that will be subject to poor shipping quality and reduced longevity (Jones, J.B., 1998; Resh, H.M., 2001).

Symptoms of stress can also occur from non-nutritional factors. Cool root temperatures, inadequate moisture, physical damage from insects, disease, and applied foliar chemicals can produce symptoms similar to nutritional insufficiencies. Controlled-environment agriculture (CEA) practices, discussed earlier, strive to establish process controls to ensure ideal growing conditions. In particular, horticultural practices that are conducted without soil such as hydroponics and aquaponics require constant monitoring and process control to maintain ideal conditions due to the lack of the soil medium which frequently can buffer against nutrient deficiency and toxicity alike (Jensen, M.H. & Collins, W.L., 1985; Resh, H.M., 2001).

Hydroponics systems require daily monitoring and constant control of ideal growing conditions to ensure maximum yields. Additionally, because plants are traditionally grown in close proximity to each other and in high density, extra measures must be taken to prevent the proliferation of plant diseases and pests which could severely impact an entire operation (Jensen, 1985). Thus, the use of high quality water is warranted for hydroponics operations. To monitor the condition of plants and liquid nutrient solution in a hydroponics system, growers can utilize a variety of testing kits and equipment. Indicators of nutrient solution quality and environmental conditions can also be expressed by plants. Experienced growers can detect signs of stress by observing physical characteristics of plants (see Table 7 below).

Table 7 Terminology used in the description of symptoms of plants (from (Resh, H.M., 2001)

Term	Description
Localized	Symptoms limited to one area of plant or leaf
Generalized	Symptoms not limited to one area but spread generally over entire plant or leaf
Drying (firing)	Necrosis – scorched, dry, papery appearance
Marginal	Chlorosis or necrosis – on margins of leaves initially; usually spreads inward as symptom progresses
Interveinal chlorosis	Chlorosis (yellowing) between veins of leaves only

Table 7 (continued)

Mottling	Irregular spotted surface –blotchy pattern of indistinct light and dark areas; often associated with virus diseases
Spots	Discolored area with distinct boundaries adjacent to normal tissue
Color of leaf undersides	Often a particular coloration occurs mostly or entirely on the lower surface of the leaves, i.e. P deficiency - purple coloration of leaf undersides
Cupping	Leaf margins or tips may cup or bend upward or downward, i.e. Cu deficiency - leaves curl into a tube; K deficiency - margins of leaves turn inward
Checkered (reticulate)	Pattern of small veins of leaves remaining green while interveinal tissue yellows (Mn deficiency)
Brittle tissue	Leaves, petioles, stems may lack flexibility, break off easily when touched (Ca or B deficiency)
Soft tissue	Leaves are very soft, easily damaged (excess N)
Dieback	Leaves or growing point dies rapidly and dries out (B or Ca deficiencies)
Stunting	Plant is shorter than normal
Spindly	Growth of stem and leaf petioles are very thin and succulent

2.2.1.1 Macronutrients

The nine elements, C, H, O, N, P, S, K, Ca, Mg, have been designated as macroelements because they are found and required in substantial concentrations compared to the remaining seven elements referred to as *micronutrients*. Carbon, hydrogen, and oxygen are supplied by water and from the atmosphere. Atmospheric nitrogen, N_2, comprises the major part of air, yet only very few plant species have developed methods for synthesizing atmospheric nitrogen. Nitrogen, phosphorus, and potassium are common nutrients of interest for plant growth and fertilizer producers sell products with various N:P:K ratings that signifies the amount of each nutrient by mass percentage (Epstein, E. & Bloom, A.J., 2005; Jones, J.B., 1998). In green plants, the three major elements are combined in the process of photosynthesis. In order for photosynthesis to take place:

- The plant must be nutritionally sound

- The plant must not be under water stress
- The leaf surface must be exposed to sunlight
- The stomata must be open

Nitrogen comprises a large quantity of necessary organic compounds, including amino acids, proteins, coenzymes, nucleic acids, and chlorophyll. Nitrogen is utilized by the plant in the forms of NO_3^- and NH_4^+. The uptake of nitrate ions stimulates the uptake of cations in the plant. Contrarily, the uptake of ammonium ions restricts cations, leading to deficiencies in Ca and K. In anaerobic soil conditions, nitrite (NO_2^-) can exist; nitrite is toxic to plants at very low levels (<5 ppm) (Jones, J.B., 1998). Plants deficient in N exhibit slow growth, weakness, will be stunted, mature early, and have significantly reduced yield quantity and quality. Excess nitrogen results in richly green colored, succulent foliage that is highly susceptible to disease and insect infestation. If nitrogen is supplied mainly as NH_4^+, a toxicity condition can develop that result in the degradation of vascular tissue, consequently restricting water uptake (Jones, J.B., 1998).

Phosphorus is an essential, irreplaceable element in all living organisms as it is a major component in adenosine triphosphate (ATP), ribonucleic acids (RNA), deoxyribonucleic acids (DNA), and phytin (Johnston, A.E., Poulton, P.R., Fixen, P.E., & Curtin, D., 2014). Highest concentrations of P are found in new leaves. P deficiency yields slow, stunted, and weak growth as well as purple pigmentation on the underside of older leaves characteristic of P deficiency. Excess P results in micronutrients deficiencies of most notably, Fe or Zn (Johnston, A.E. et al., 2014; Jones, J.B., 1998).

Potassium is involved in maintaining water pressure within plant cells and opening and closing of plant stomata. Most plants absorb more K than what is needed, an activity known as *luxury consumption*. High K content can lead to Mg and then Ca deficiencies. K deficiency yields sensitivity to disease infestation, lodging, and older leaves will appear as if they have been burned along the edges (see figure 30). K deficiency can also lead to ammonium toxicity should NH_4^+ be present.

Calcium is necessary for maintain cell integrity, membrane permeability, enhancing pollen germination supports healthy plant growth. Calcium is also reported to detoxify the presence of heavy metals within a plant (Jones, J.B., 1998). Ca deficient plants exhibit dieback, abnormal growth of new leaves, and significantly reduced quality of fruit. Excess Ca will induce a deficiency of the other important cations of K and Mg. Magnesium is a component of the chlorophyll molecule and other enzymes. Mg content in leaves increases with plant age. Mg deficiency yields interveinal chlorosis, beginning on older leaves and spreading to younger leaves, ultimately leading to necrosis (Jones, J.B., 1998).

Sulfur is the last of the major nutrients as it is involved in the synthesis of proteins, comprises many essential organic molecules, and reduces the risk of disease in plants. Sulfur is utilized mainly in the form of sulfate SO_4^{2-} and when it deficiency can yield generalized light yellow-green coloring of the plant and fruits, extended root growth, and woody stems.

2.2.1.2 Micronutrients

The seven micronutrients: Boron, chlorine, copper, iron, manganese, molybdenum, and zinc are found and required in relatively low concentrations compared to the macronutrient elements but nonetheless are essential to optimal growth. Sufficiency ranges are relatively large for the micronutrients but can vary based on plant species (Resh, H.M., 2001). Generally, Cl, Cu, Fe, and Mn are involved in photosynthesis and thus have direct effects on overall plant growth and yield. Cu, Fe, Mn, and Zn are associated with various enzyme functions; Mo is need for nitrate reductase only. B is utilized by the plant reproductive system and carbohydrate chemistry (Jones, J.B., 1998).

2.2.2 CEA Systems

2.2.2.1 Hydroponics

Considered to be one of the most elementary forms for growing plants, hydroponics systems are able to grow large volumes of crops in a significantly smaller area than conventional farming. Generally grown in a greenhouse as opposed to outside, the environment inside controls and is free from exposure to the elements. A hydroponics system is a system that relies on the use of nutrient enriched additives, to supply the nutrient needs necessary to support crop growth. Plants lay their roots in an inert growing medium, which can vary from air to rocks, with the exception of soil. Many systems require the use of air stones and submersible pumps to circulate nutrients, and supply dissolved oxygen to the root zone (Ernst, J.V. & Busby, J.R., 2009).

Hydroponics systems have many advantages associated with their utilization for urban agriculture applications. The roots of the crops are fully submerged in the nutrient enriched liquid solution, thus use less water which is ideal for developing countries and water scarce regions. Additionally, certain parameters may be controlled that are otherwise difficult to control in soil growing systems. The pH and alkalinity of the liquid solution can be closely monitored, allowing for ideal plant pH to be controlled, avoiding the occurrence of nutrient lockout. Also, nutrient concentrations may be closely monitored allowing operators to apply the right amount of nutrients (primarily nitrogen, phosphorus, and potassium) at key intervals respective to the various growing phases of the plant. Hydroponics systems have been associated with cleaner roots and cleaner leaves and It is not necessary for these types of systems to undergo crop rotation and other traditional farming methods that were employed to maintain soil fertility, allowing for quick crop turnaround and reestablishment of crops in a much shorter timeframe. Due to the fact that nutrients are enclosed within growing containers, contrary to traditional farming methods, the opportunity to cause runoff of nutrients also diminishes (Ernst, J.V. & Busby, J.R., 2009).

While hydroponics boasts many advantages in crop production, these systems prove expensive. Hydroponics systems generally have a capital investment associated with the purchase of new equipment: pumps, aerators, and fertilizers. In these systems, all plants are grown in close proximity; if one plant in the system becomes compromised with disease, the chances of that disease proliferating and destroying the rest of the plants increases. Hydroponics systems generally require pumps and aerators; electricity is thus a major component to hydroponics systems which may deter from its implementation, especially in urban areas of developing countries where resources such as energy may not always be in constant supply (Ernst and Busby, 2009).

2.2.2.2 Aquaponics

Aquaponics is the practice which integrates both aquaculture and hydroponics. Instead of supplying a nutrient enriched solution to grow plants in a hydroponics system, or filter and discharging polluted water from an aquaculture system, the system utilizes biological processes to produce and recycle nutrients. Aquaponics systems operate by balancing nutrient generation from fish waste with nutrient uptake by plants to achieve proper water quality (Al-Hafedh, Y.S.,Alam, A. & Beltagi, M., 2008). The water used in an aquaculture system is rerouted to become the nutrient enriched solution for plants grown in hydroponics grow beds. The plants used the solids and other nutrients derived from fish waste and use it as the nutrient source to grow and stabilize. The plants utilize the excess nutrients and return the purified water back to the tank containing the fish. Pesticides are not generally used in aquaponics systems, so it is sometimes referred to as an organic food production method that yields products produced from both aquaculture and hydroponics systems. Aquaponics systems are a viable option for treating the waste from the fish in a cost effective manner, while returning another usable product in the process (Al-Hafedh, Y.S. et al., 2008).

While aquaponics systems produce two different types of food, fish and vegetables, these systems also adopt the difficulties of both systems in addition to others. The balance between raising fish and crop production is a delicate balance where any change in the system can jeopardize the yield of either food product. If plants are not able to effectively remove the pollutants that are produced by the fish, it may be returned to the tank containing the fish. The accumulation of pollutants can have devastating effects on the fish population, such as fish kills. If the fish die, nutrient production will cease, limiting the nutrients available to plants, thus slowing their growth. Constant monitoring is necessary to ensure the correct balance of water, nutrients, and ideal conditions for both systems.

2.2.3 Fertigation Systems

Fertigation is defined as the application of fertilizer with irrigation water. The practice of fertigation is of special interest to small local farmers engaged in the local food movement which is gaining popularity in the United States. Fertigation grants farmers precise control over the quantity, location, and time fertilizer is applied catering to the needs of different plant groups in different growth stages. Such control allows for the cultivation of various crops in a small area, perfectly suitable for meeting the demands of local produce operations and community supported agriculture (CSA) programs (DeValerio, J., Nistler, D., Hochmuth, R., & Simmone, E., 2012).

Drip irrigation, also known as micro irrigation, or trickle irrigation is the most common form of fertigation for fresh market vegetable production. Fertigation via drip irrigation, applies dissolved fertilizer and water directly to the soil, using generally less than half the water of overhead and furrow irrigation (Miles, C., Roozen, J., Maynard, E., & Coolong, T., 2012). This water use efficiency is due to the water soaking into the soil before evaporating and because water is applied only where it is needed. Precise watering such as drip irrigation reduces the spread of weeds and the amount of nutrients that runs off to receiving water bodies. Additionally, irrigation water contact with the above ground crop is minimized yielding less favorable conditions for disease. Avoiding above ground contact with the plant also enhances safety associated with irrigating with reclaimed wastewater (Miles, C. et al., 2012; WHO, 2006; Yermiyahu, U.,Ben-Gal, A. & Dag, A., 2014). Well maintained drip irrigation systems are a requirement for successful fertigation.

2.3 Wastewater Use in Agriculture

Humans consume nutrients from plants and other foods, yet not all the nutrients consumed are utilized. Unutilized nutrients exit the body through excreta. Almost all nutrients that a person takes in over the course of a year will reappear in the excreta which is then conveyed in the wastewater infrastructures of the developed world, or released to the environment in areas lacking proper sanitation (Drangert, J., 1998) Table 2 displays the typical dry mass content of various constituents in wastewater. The nutrient content within excreta has promoted its use as fertilizer in regions where either nutrient fertilizers or the capitol to purchase them are scarce. The practice of wastewater use for agricultural purposes has long been established in developing countries where public health is does not rank as high of a concern as agricultural productivity that sustains livelihoods economically (WHO, 2006). Various methods have been employed in developing countries to utilize raw waste water for agricultural use. In the United States, public health concerns combined with the lack of infrastructure in the nexus of wastewater treatment and agriculture industries have limited the use of wastewater for agricultural applications. However, there do exist regions in the U.S. that have experienced success using reclaimed water for agricultural production, Monterey County, CA being a prime example where more than 5000 ha. of lettuce , broccoli cauliflower, fennel, celery, artichokes, and strawberries have been irrigated with recycled water for more than a decade (EPA, 2012).

2.3.1 Methods

The urine of healthy individuals contains very few pathogens, where in contrast feces may contain millions of pathogens (Drangert, J., 1998). No mix toilets can collect urine which can be applied to crops after 6 months of storage to ensure that all pathogens which may have been collected in the system from the accidental exposure to fecal matter are neutralized prior to plant application. The pathogenic bacteria are usually inactivated in two to three months; six months is recommended to ensure safe use. Inactivation of pathogens is caused by various factors: long exposure to high PH (above 9), lack of substrate, and natural death (Drangert, J., 1998). While urine can be used for irrigation, direct application to edible plant parts is not recommended (WHO, 2007).

An average human expels approximately 500 liters of urine in a year, expelling an additional 18-25 kg of solids contained in the urine. The solids are generally organic matter, containing nutrients that can be used for crop growth. Large amounts of urine can replace a large amount of the water requirements needed for crop growth, especially within the household level. Direct urine use utilizes pure, undiluted urine as the water source in the growing area. Several no mix toilets have the feces bowl attached to sewer lines where it will be transported for treatment or disposal while the urine bowl attaches to a drainage line which stores the urine in tanks to be used as fertilizer at a later date (Drangert, J., 1998).

Urine separation practices are a prime example of sanitation and reuse, which is practiced throughout China, Central America, and Sweden.

Diluted urine lowers the overall concentration of nutrients but will not lower the overall quantity of nutrients. Salinity is a major factor that may affect plant growth, but diluting urine can mitigate the effects of high salinity. Results have shown decreased plant growth with the use of mixtures containing 30% or greater urine content. Plants irrigate with more dilute solutions showed higher plant growth in terms of plant height as well as leaf (Kocatürk, N. & Baykal, B., 2012).

The use of human excreta as a source of nutrients is growing with urban slums in the practice of urban agriculture. Many farmers that use human excreta as the nutrient source can testify to the benefits of using excreta, especially in areas where soil conditions are dry and not ideal for growing crops. The use of treated and untreated excreta is a common practice in developing countries. According to Cofie et al (2010), the use of excreta in agriculture can have significant contributions to sustainable agriculture around urban agglomerations in developing countries. Excreta have the added benefit of rebuilding soil fertility which many times the use of mineral fertilizers alone cannot ensure the continued fertility of soils in these countries. While using mineral fertilizers are effective at growing crops, does not make the soil more fertile because it does not supply the organic matter which is heavily present in human excreta. Additionally the high cost that is generally associated with the high cost of mineral fertilizers may not provide beneficial support for communities which are living below the poverty line.

The benefits of human excreta also has adverse health effects associated with it use. The use of excreta is used both treated and untreated in many countries. Using untreated excreta has shown an increase in the exposure to the particular infections such as Ascaris lumbricoides and hookworms as well as helminthes infections from the use of excreta as a fertilizer source in agriculture (WHO, 2006). Composting presents a low cost method for treating excreta for agricultural use. Other methods include drying and storing the product until it has sat long enough to ensure the destruction of pathogens and intestinal worm eggs (Cofie, O.O. et al., 2009). Additionally co-composting of using human excreta and food waste may unlock additional nutrients and organic matter from the food waste. While the excreta may be treated, additional practice should be considered when using treated excreta as a fertilizer source. Farmers should use gloves, avoid contact with the mouth and eyes, as well as always where protective footwear when walking on or around crops that have been fertilized with excreta (WHO, 2006).

2.4 Summary

AnMBR technology combines the treatment capabilities of anaerobic digestion with the high solid separation performance of ultrafiltration membranes. This combination yields reactors with much smaller footprints and effluents of higher quality than traditional anaerobic digestion technologies. The two processes of AD and membrane filtration fare little, however in efforts to remove nutrients. The removal of nutrients prior to discharge of the effluent represents antiquated practices in the wastewater treatment industry that contributes to an unsustainable consumption of resources and linear system of water management. As George Tchobanoglous stated in his presentation, *Wastewater Treatment Trends of the 21st Century* (Tchobanoglous, G., 2013), “wastewater is a renewable, recoverable source of potable water, energy, and resources. It is time for a new paradigm to shape the way industry practices *treatment*, treatment.

Nutrients in permeate, seen as environmental burden on one hand, are seen as opportunity in another. Untreated wastewater has seen its fair share of use for agricultural purposes with its highest use in developing countries. The use of untreated wastewater for agriculture spawns a plethora of concerns over public health (WHO, 2006). AnMBR technology reduces the risk of spreading disease and presents a much safer option for irrigation. Recovered nutrients from wastewater could help decrease the demand for fertilizer production which has been facing many problems associated with nitrogen cycle imbalance and the impending situation of peak phosphorus(Johnston, A.E. et al., 2014). Furthermore, as cities continue expanding, so will the need for infrastructure to sustain high density habitation. Decentralized infrastructures, especially wastewater treatment infrastructure, can alleviate water demand while providing useful resources at the point of generation, ultimately conserving resources and enhancing the local environment (Gikas, P. & Tchobanoglous, G., 2009).

CHAPTER 3: MATERIALS AND METHODS

3.1 AnMBR Permeate

3.1.1 Permeate Generation

The reactor that generated permeate used for this study was a 20.45 liter, two-stage anaerobic membrane bioreactor designed for the treatment of domestic wastewater at ambient temperatures. Two sequenced reactors of equal volume (10.23 liters), the first of which operated as an upflow anaerobic sludge blanket (UASB), and the second as a completely stirred tank reactor (CSTR). Two membrane modules provided a total of 0.0423 m^2 of membrane surface area. Tubular ultrafiltration membranes (Pentair, X-flow modules) made of polyvinylidene fluoride (PVDF) and with an average pore size of 0.03μm were used inside the modules. Wastewater was provided by direct extraction from the grinder station of a local elementary school's septic system. Analysis of the pilot system reactor performance is included in another study by Bair et al. (pending publication).

3.1.2 Permeate Analysis

Evaluation of the performance of the pilot scale AnMBR system included the analysis of permeate produced for nutrient content (TN, TP, total ammonia) which was conducted using HACH test kits (HACH Loveland, CO). Alkalinity of permeate and pH was measured using a pH probe.

3.1.3 Microbial Analysis

Fecal coliforms and *E.coli* testing was performed using the USEPA's membrane filtration protocol (method 10029). Fecal coliform testing was performed using the USEPA's membrane method

8074. In addition to feed, reactor 1, reactor 2, and permeate samples, the microbial testing included feed that had been preheated to 65^0C and permeate that underwent chlorination at 500ppm NaOCL.

CHAPTER 4: HYDROPONIC GROWTH STUDY

4.1 Introduction to Experiment

The re-use of wastewater is becoming accepted more and more as a legitimate practice to confront the challenges of water scarcity and environmental degradation com, two challenges that will only be further exacerbated by a growing population and a changing global climate. The global trends of populations migrating towards cities foreshadow situations of concentrated water issues in urban centers. Concentrated water demands warrant the implementation of sustainable water management practices such as reclaimed water usage (Gikas, P. & Tchobanoglous, G., 2009). Additionally, the limited access to high quality food at high quantities hints at the deteriorating state of food security in urban centers. The lack of food security results in malnutrition, especially amongst the urban poor. Strategies aimed at enhancing agricultural productivity and food availability can positively impact food security.

AnMBR are capable of treating highly concentrated wastes while recovering valuable resources for local use. The permeate produced by AnMBR systems contain nutrient elements that can prove useful in agricultural and/or landscaping operations as fertigation/irrigation water. This experiment proposes the direct usage of AnMBR permeate as nutrient solution for a hydroponics system and serves to assess the performance of permeate to that exhibited by a control fertilizer solution. This integration of onsite wastewater treatment with hydroponics production represents sustainable management practices that conserve water and recovers energy and nutrient resources for immediate use on site.

4.2 Hydroponic Growth Trials

4.2.1 Greenhouse Trial

Figure 11 Photo of cucumber plants in hydroponic grow cells

Cucumber plants were grown in a greenhouse at a local charter school, Learning Gate Community School, to simulate growth in an outdoor environment. Five equivalent sized tubs (grow beds) were filled with five liters of solution with a 6” aeration stone. Four slotted cups (grow pods) were placed on a sheet of Styrofoam in order to allow the plants to float on the liquid surface. The grow pods were then filled with clay pellets and a single cucumber seed was placed in each grow pod. After seven days of initial growth in blank solution, initial measurements were taken and the water was switched to the five different solution: pure permeate (P1), 50%dilution of permeate (P0.5), a control solution (C1) obtained from a commercially available hydroponic nutrient product (MaxiGro™, General Hydroponics, Sebastopol, CA), a 50% dilution of the control solution, and a blank solution . Plants were measured every Monday, Wednesday, and Friday of the week. On Monday, a sample of the solution was taken, prior to removing the solution from the week prior and refilling with fresh solution. Another sample was taken immediately after the addition of fresh solution. Plant growth measurements included:

- Plant height, measured from grow pod to top of plant
- Number of leaves
- Stem width, measured at plant base

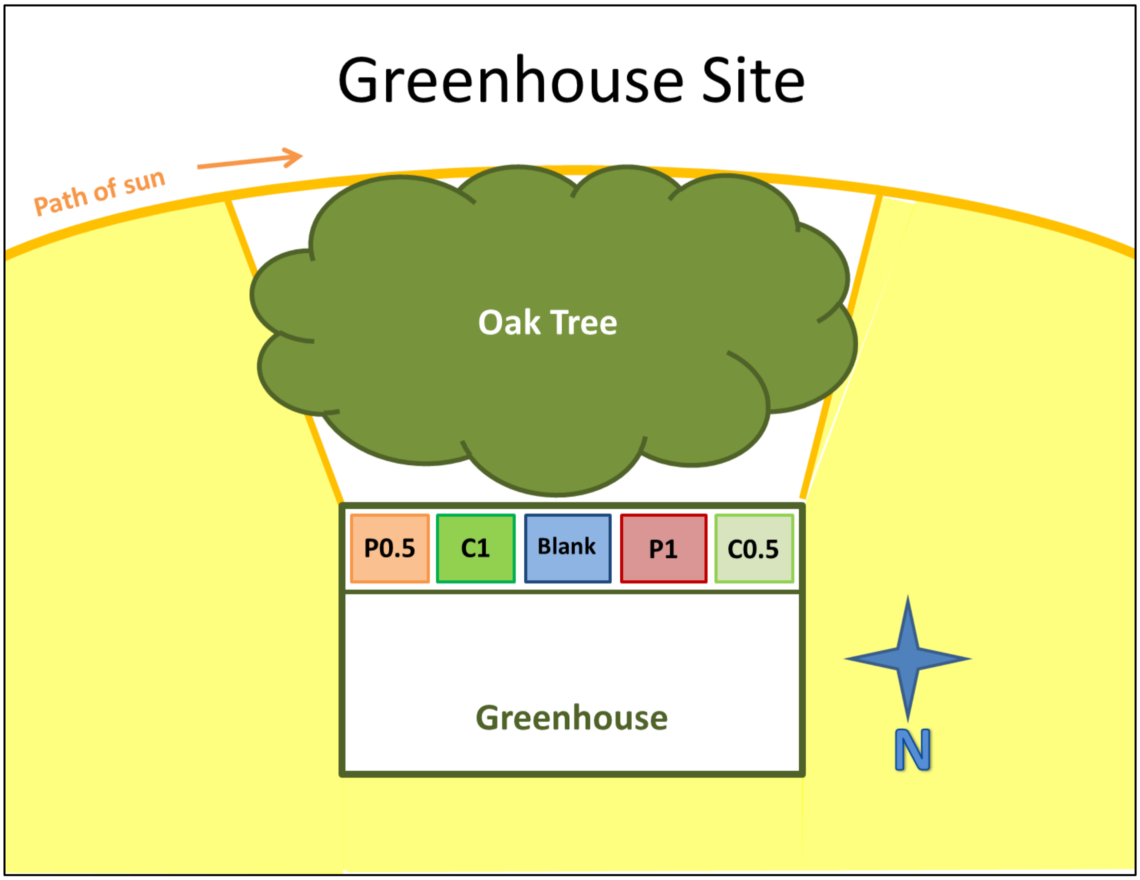

Figure 12 Plan view of greenhouse site

4.2.2 Laboratory Trial

A total of 18 tomato plants were grown indoors in a static solution culture[4] configuration using six different liquid nutrient solutions. Tomato plants were grown in a 1 liter liquid volume of solution with continuous aeration; the solution was regenerated every 7 days. The nutrient solutions used included permeate from a pilot scale anaerobic membrane bioreactor (AnMBR) labeled "P1". The control solution used was a commercially available hydroponic nutrient blend (MaxiGro™, General Hydroponics, Sebastopol, CA) labeled C1. Tap water was used as the blank solution. Plants were also grown in 50% dilutions of the AnMBR perm solution (P0.5) and control solution (C0.5). To match the ideal pH that is recommended in hydroponic applications, the sixth solution consisted of pure AnMBR permeate that was adjusted to a pH of 6.5 using nitric acid and is labeled P1*.

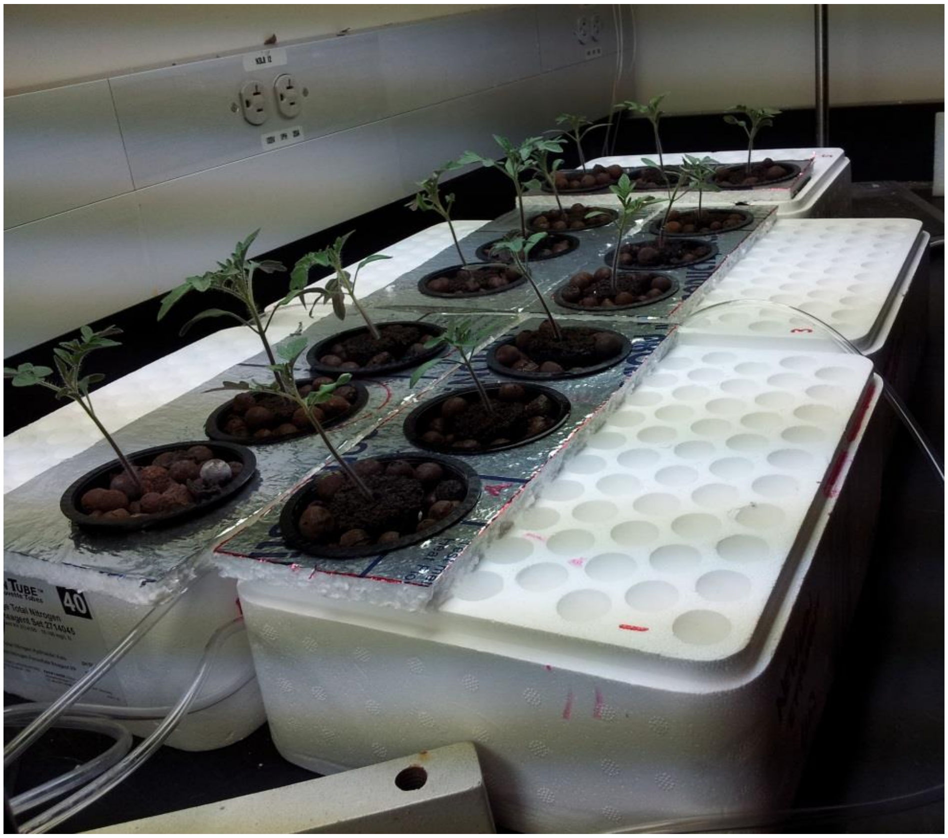

Figure 13 Tomato seedlings after transplant to grow cells in laboratory hydroponics trial

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[4] Static solution culture describes the hydroponics technique that grows plants in containers filled with solution, with or without aeration. Plant roots are given sufficient headspace in the reservoir to receive oxygen.

The experiment was conducted indoors in an indoor greenhouse to discourage the influence of nearby indoor activities. 30 tomato seeds were started using Ready Gro™ super plugs (Botanicare, LLC. Chandler, AZ). Lighting was supplied by two SS Sun Blaze™ T5 4' w/ 4 Lamps (Sunlight Supply, Inc., Vancouver, WA) which had a maximum output of 20,000 lumens. During the seed starting phase, seeds were exposed to 14 hours of light followed by 10 hours of darkness. Once transferred to growth tray configurations, light/dark schedules were adjusted to 12 hours of light, 12 hours of darkness.

After 12 days, 18 healthy plants were transferred to the static solution culture growth trays. Seedlings were placed in 3-inch plastic net cups (Sunlight Supply, Inc., Vancouver, WA) filled to volume with hydroton (expanded clay pellets) to secure the plug. Three plants were placed in a rectangular Styrofoam container measuring 9 cm x 26 cm x 8 cm comprising one grow cell. 1 liter of aqueous solution was added to the grow cells weekly. Water was added intermittently to maintain liquid level. The three net cups in each growth tray were suspended above solution using 3/4” Styrofoam. Each grow bed contained a 6” aeration stone submerged in the aqueous solution that operated continuously. Figure 11 shows a diagram of the static solution culture configuration used.

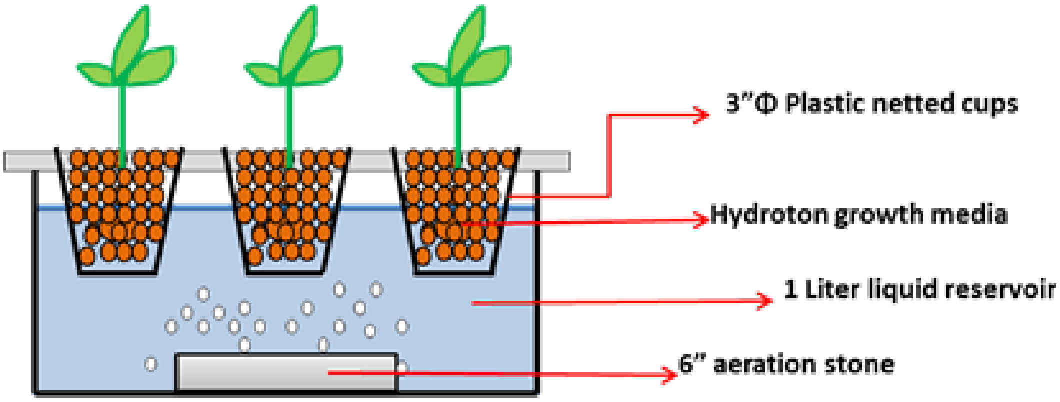

Figure 14 Diagram of static solution grow cell

The height of each plant as well as the number of leaves on each plant was recorded every other day for 33 days. On the final day of the testing period, height and leaf count measurements were taken as well as the number of blooms and fruits. Wet and dry weights of the root and shoot portion of each plant were also measured. Shoots were severed at the location just above the grow plug. Root and shoot materials were weighed immediately after harvesting to record fresh weight. Root and shoot material was then dried in an oven at 103°C for 24 hours.

4.3 Hydroponics Growth Results and Discussion

4.3.1 Greenhouse Trial Results

The results of the greenhouse trial are displayed below in Figures 15–21. The labeling convention used in the plots is as follows: control solution (C1), pure permeate (P1), 50% dilution of control solution (C0.5), 50% dilution of permeate (P0.5), and a blank solution of tap water (blank).

Plants grown in the control solution displayed attributes of optimal growth in all measurements while all other treatments yielded significantly reduced growth. The effects of nutrient deficiency were further exacerbated by non-ideal environmental conditions such as fluctuating temperature and variable light distribution.

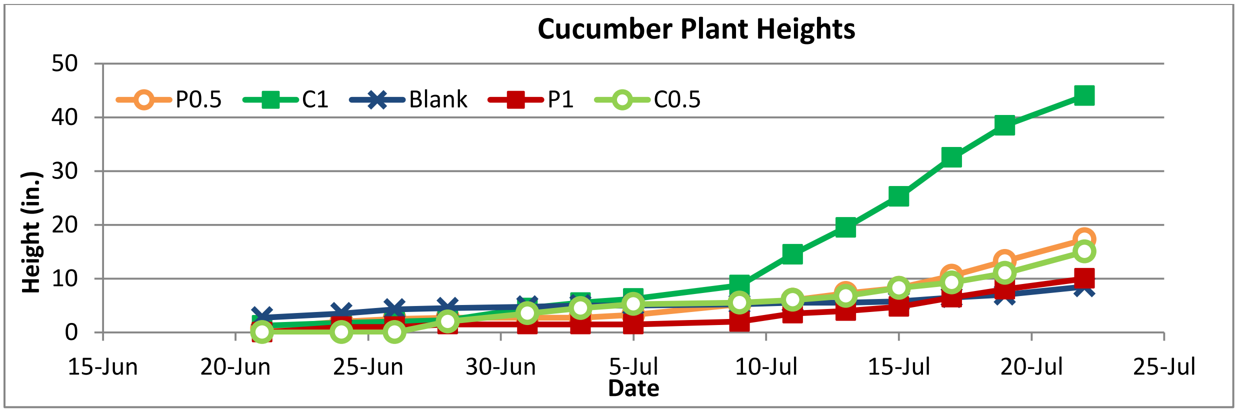

Figure 15 Plot of cucumber plant lengths in each grow bed

Figures 15 and 16 display the optimal growth achieved by the control solution. Growth performance of the control solution is most notable in the overall lengths and leaf counts achieved by plants grown in the control solution.

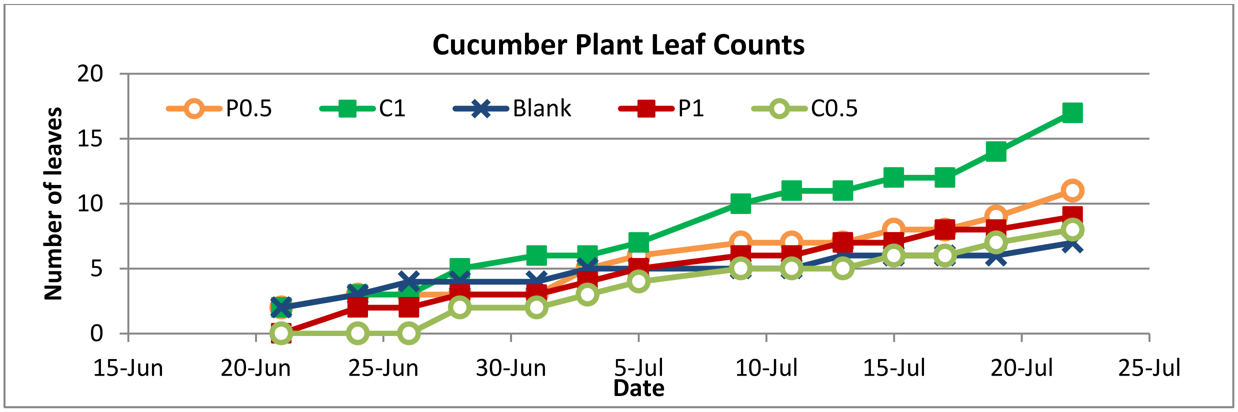

Figure 16 Plot of cucumber plant leaves

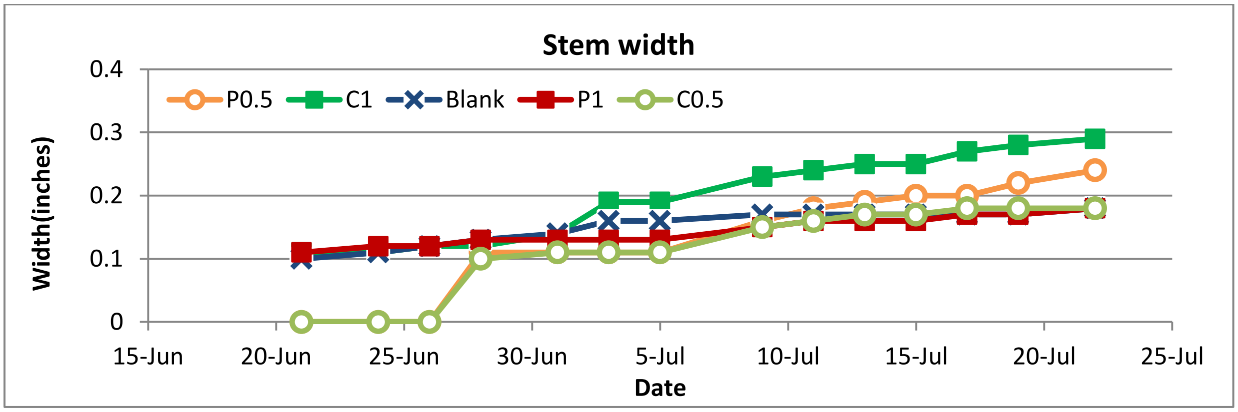

Figure 17 Plot of cucumber plant stem widths

Cucumber growth behavior remains consistent for each parameter measured. The measurement of stem width provides insight on the rate of vegetative growth. The results show diluted permeate (P0.5) to be achieving the second best growth performance. Plant height, stem diameter, and leaf count are all parameters of vegetative growth which is facilitated most by nitrogen (Jones, J.B., 1998; Stefanelli, D.,Goodwin, I. & Jones, R., 2010).

Vegetative growth is promoted further by photosynthesis which assimilates carbon into plant biomass. Grow cells receiving the most light were the P0.5 and C1 grow cells which received the most UV radiation in the morning hours. An oak tree placed just south of the greenhouse reduced exposure to sunlight throughout the late morning-early afternoon hours of the day (see Figure 12). This could explain why P0.5 experienced the second best plant growth as it received the most sunlight but growth was reduced by the lack of optimum nutrition.

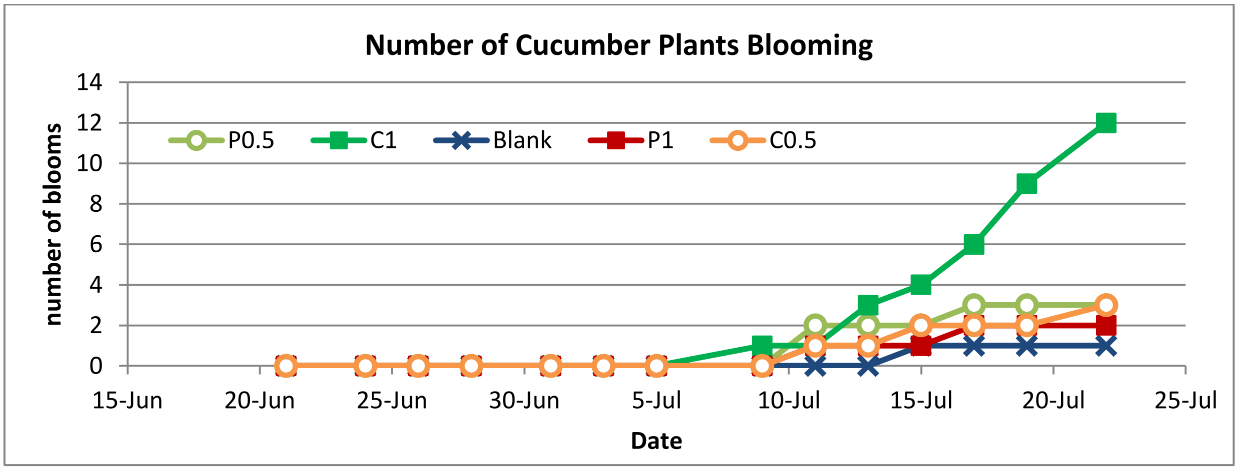

Figure 18 Plot of cucumber fruit appearance

Bloom count data shows diluted permeate and diluted control performing similarly. This could be due to the fact that the diluted control solution, while receiving less sunlight, still had more favorable nutrient concentrations thus could accomplish reproductive growth in less than favorable lighting conditions. These results further support the advantage of increased sun exposure as it served to equalize blossom development in the undernourished plants.

The control solution mixture was derived from a commercially available hydroponic nutrient fertilizer thus all nutrients needed for optimum growth are in abundance. Nutrients recovered by the AnMBR system were unable to consistently reach the same concentration as those of the control solution, thus implying decreased production is to be anticipated in plants receiving nutrition from AnMBR permeate.

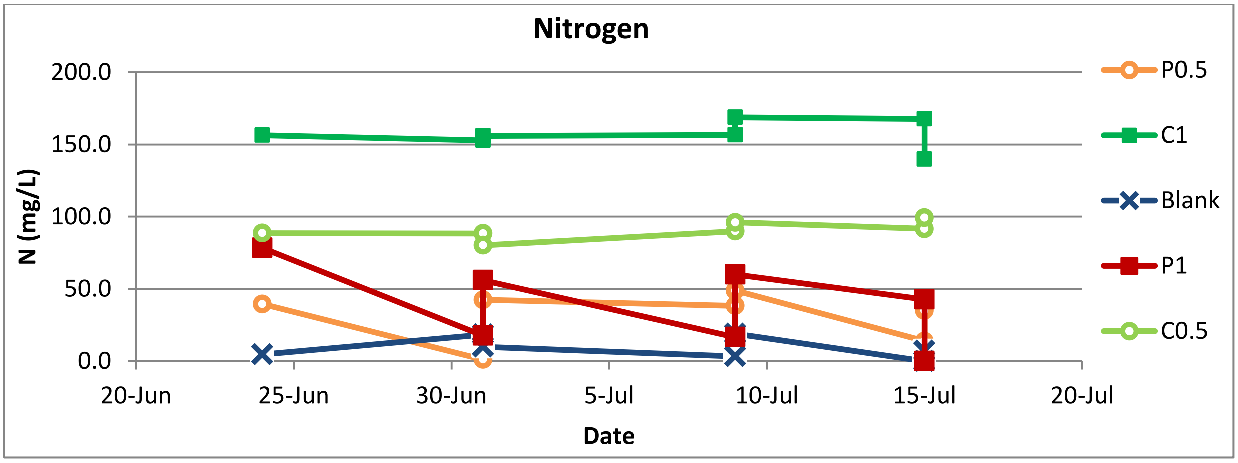

Figure 19 Total Nitrogen concentrations in grow solutions

Results from total nitrogen (TN) testing indicate permeate N-concentrations to be at lower concentrations than that of the diluted control solution (see Figure 19). However, total ammonia test results (Figure 20) indicate permeate ammonia concentrations to be higher than reported concentrations for total nitrogen.

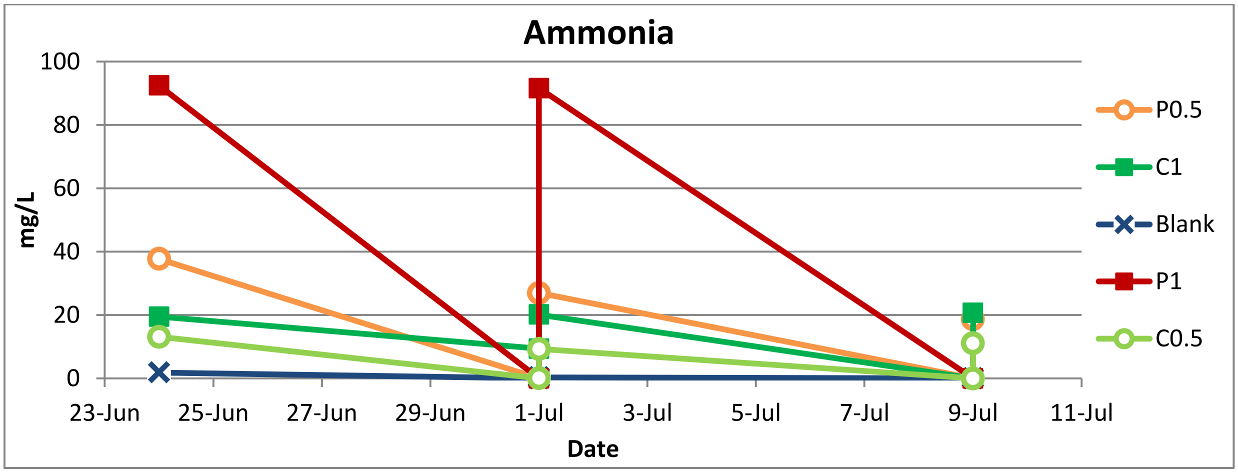

Figure 20 Ammonia concentrations of growth solutions

Figures 19 thru 21 show nutrient concentrations at the beginning and end of the first and second week of the experiment which signifies nutrient concentration immediately after replacing the nutrient solution and immediately prior to discarding old solution in an attempt to track nutrient uptake.

Results of ammonia concentration raise suspicion as ammoniacal nitrogen does not seem to be accounted for in either TN measurements or increased plant growth. The high temperature of the greenhouse environment could have encouraged the volitization of ammonia thus decreasing ammonia concentrations. The grow cell configuration that was utilized left some water surface expose to the atmosphere, further enhancing the possibility of both evaporation and volatilization.

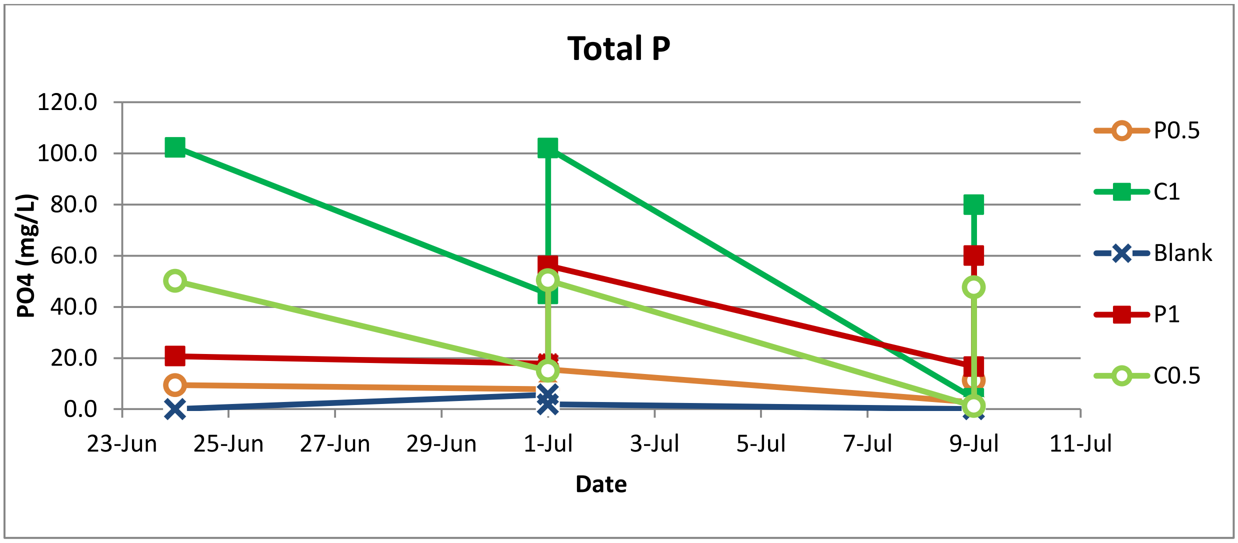

Figure 21 Total phosphorus concentrations of grow solutions

Concentration of phosphorus lower than that of the control solution phosphorus concentration most certainly contributed to the reduction in growth that was experienced by all plants except the control. Phosphorus levels in permeate began to increase. The fluctuating nutrient content of wastewater treated by the AnMBR system indicates the need for equalization of nutrient content prior to utilization in hydroponic applications. In addition to nutrient equalization, process control measures should be implemented to control the release rate and concentration of nutrients to be used for hydroponic cultivation.

The evidence of disproportional sun exposure in addition to the lack of controls over environmental conditions warranted a second hydroponic growth trial to be conducted indoors, where light, temperature, and relative humidity can be kept relatively constant. The results of the subsequent laboratory study are in the following section.

4.3.2 Laboratory Trial Results

The laboratory trial of hydroponic growth utilized the same labeling convention with the addition of a sixth nutrient solution of permeate that was adjusted to a pH of 6.5 with nitric acid (P1*).

Permeate solutions performed better indoors under controlled conditions with best growth experienced by plants grown in the pH adjusted permeate (P1*). P1* experienced growth rates on par with that of the control solution (as seen in Figures 22 and 24).

Results of leaf counts echo the results of plant height with diluted control solution experiencing reduced performance. Reduced vegetative growth is associated with less than ideal concentrations of important macronutrients: N, P, and K (Epstein, E. & Bloom, A.J., 2005).

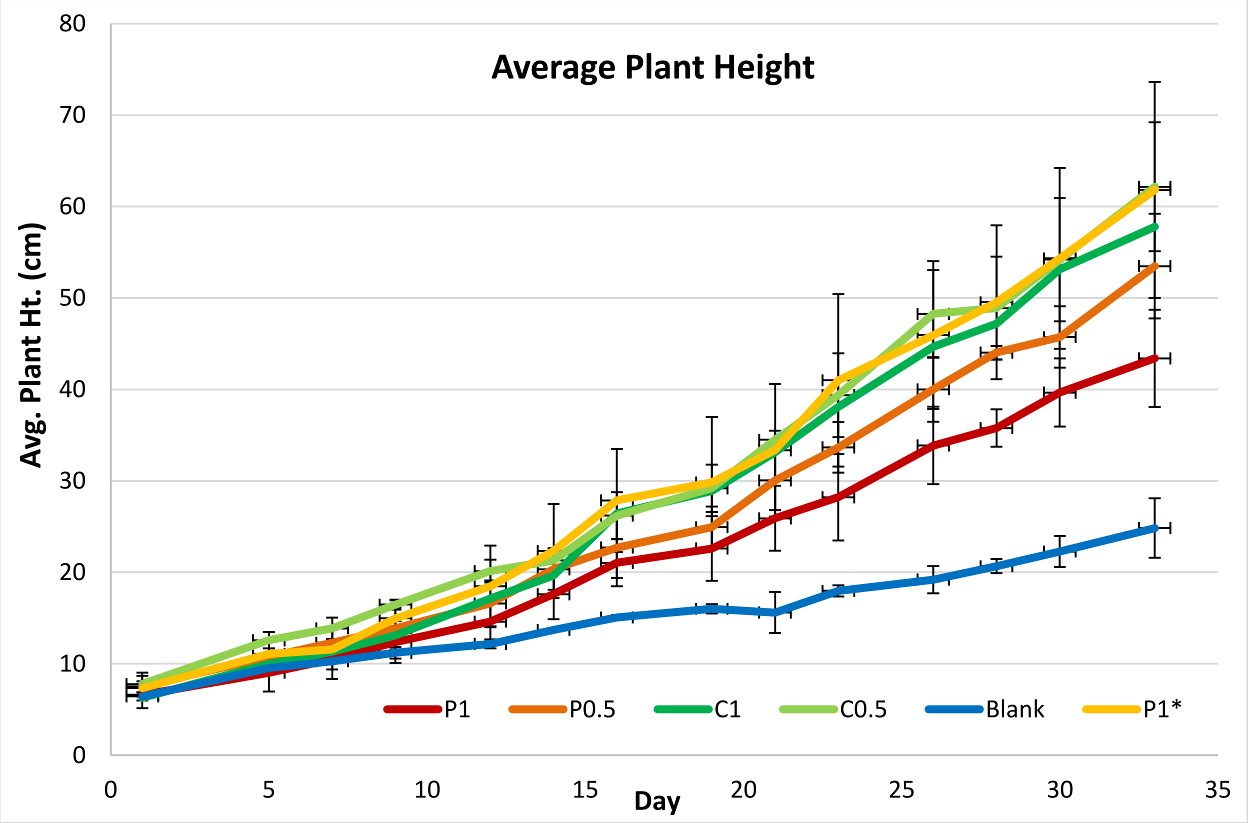

Figure 22 Tomato plant height developments over time

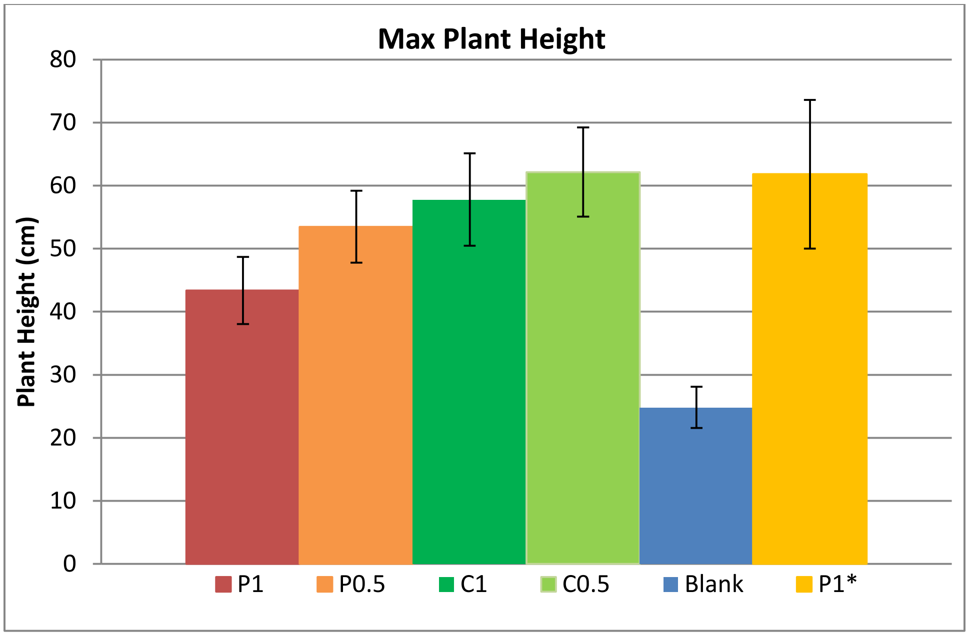

Figure 23 Average final heights of tomato plants with standard deviation

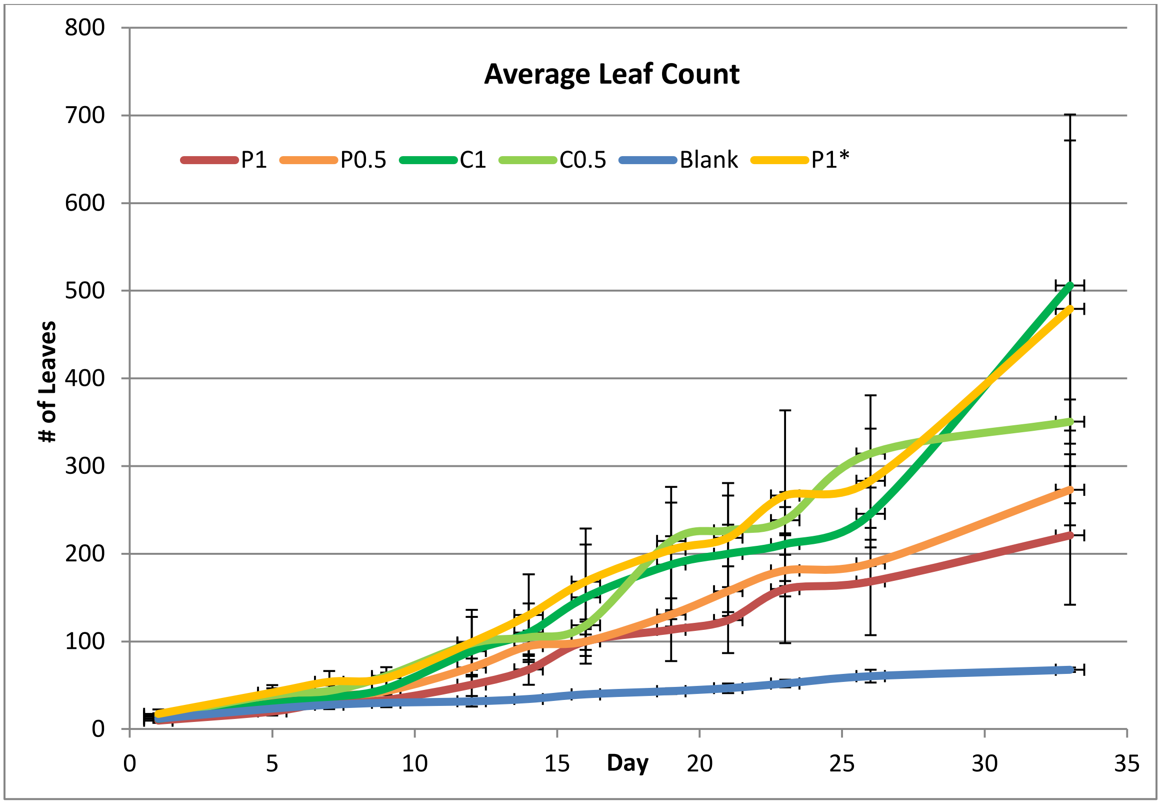

Figure 24 Average number tomato plant leaf developments over time

The control solution conveyed optimal reproductive growth with the highest average bloom formation by the end of the experiment. Figure 26 displays the final number of blooms that developed as well as the variation experienced between the three plants grown in each nutrient solution. P1* displays high variability in measured plant parameters.

The purpose of this growth experiment was to compare the plant growth performance of AnMBR permeate with that of a control fertilizer solution when used in a hydroponics system configuration. This comparison is best conveyed in Figure 27 where plant growth indicators were used to create a composite index of the laboratory trial results.

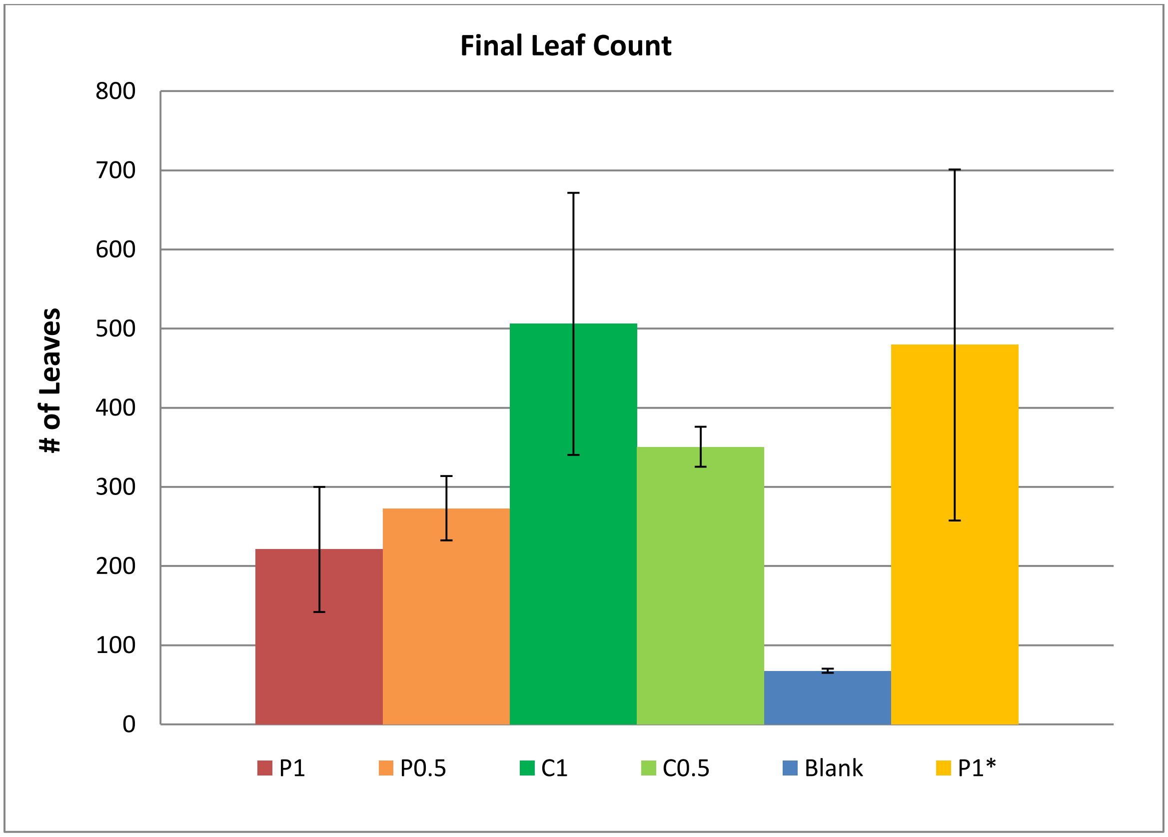

Figure 25 Final average leaf counts of tomato plants with standard deviations

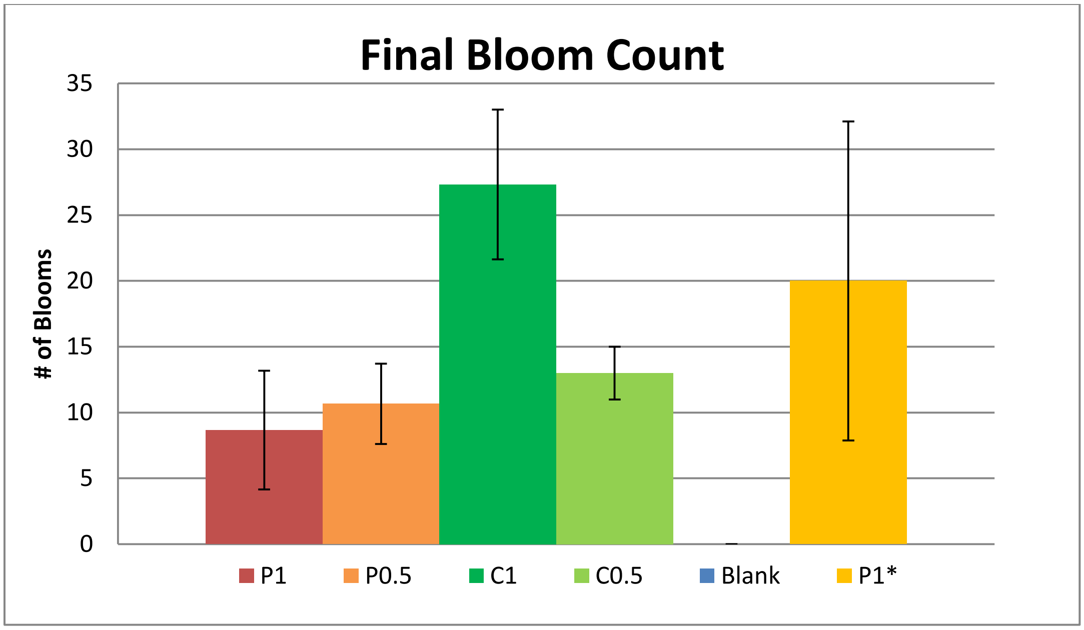

Figure 26 Average final bloom counts of tomato plants

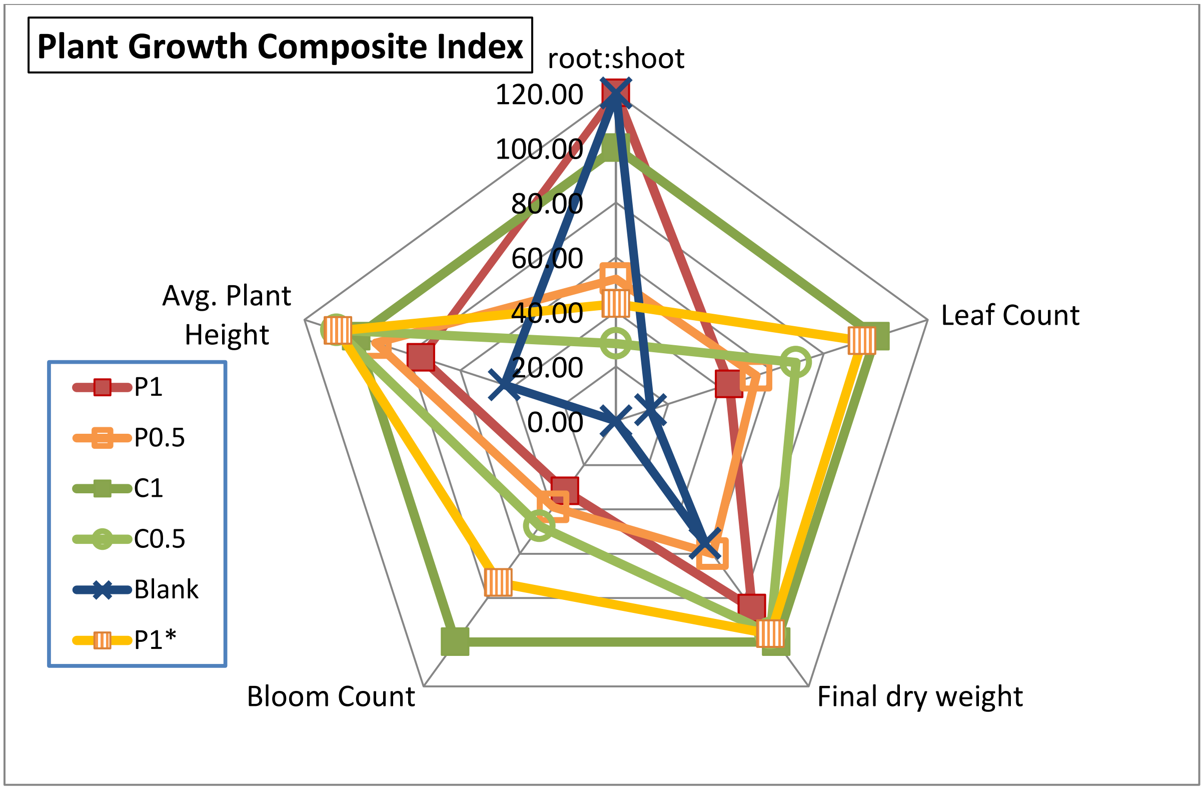

Figure 27 Plant growth composite index comparing various growth parameters with the control growth solution

Figure 28 First fruit set in P0.5 solution

Results achieved by the control solution were considered to be optimal and set at a value of 100%. Values achieved by other solutions represent a percentage of the control values. The composite index allows for quick perception of permeate performance relative to that of the control.

The results indicate that permeate from the AnMBR system can yield viable tomato plants but minor alteration is necessary. Tomato plants growing in the pH adjusted permeate solution did not develop extensive root systems like that of the control group, yet the plants displayed adequate health in regards to leaf count, plant height, bloom count, and color. Another observation to note is that the only groups of plants to experience the setting of fruits were the plants grown in diluted permeate (Figure 28).

Table 8 Nutrient concentration of control solution

Control Solution			
NH4 (mg/L)	**TP (mg/L)**	**TN (mg/L)**	**TK (mg/L)**
28.125	93.75	187.5	262.5

Table 9 Average nutrient concentrations of AnMBR permeate

AnMBR Permeate			
Conc.	**NH4 (mg/L)**	**TN (mg/L)**	**TP (mg/L)**
Avg.	172.9	188.9	51.3
SD	118.4	151.9	28.4

All plants grown using AnMBR permeate solutions exhibited positive growth with minor signs of stress caused by either a slight nutrient deficiency or toxicity. Figure 27 shows that tomato plants grown in permeate and permeate with nitric acid treatment achieved 84% and 96% of the control plants' final dry weights, respectively. However, bloom counts of plants grown in pure permeate and diluted permeate were significantly lowered (31% and 39% of that of the control, respectively), indicating a nutritional insufficiency. Abundance of nitrogen fertilization has been shown to affect blossom development by promoting vegetative growth instead of reproductive growth (Ozores-Hampton, M. & McAvoy, G., 2012). Contrarily however, tomato plants grown in permeate treated with nitric acid achieved 73% of the control plants' average bloom count. This does not support the claim that excessive nitrogen blossom production as this the plants grown in this last solution effectively received more nitrogen, but in the form of the nitrate ion whence dissociated in solution.

However, a characteristic of AnMBR permeate that must be noted is the ratio of ammoniacal nitrogen to total nitrogen (see Table 9 and Figures 19 and 20). In AnMBR permeate, $NH_4^=$ accounts for 70-80% of the total nitrogen whereas in the commercial fertilizer blend, NH_4 comprised a much lower percentage of 15% of the total nitrogen. Reduction in growth is experienced in tomato plants where NH_4 is the major form of N available for plant uptake as carbohydrate depletion can occur with NH_4 nutrition (Borgognone, D., Colla, G., Rouphael, Y., Cardarelli, M., Rea, E., & Schwarz, D., 2013; Jones, J.B., 1998). The presence of high NH_4 concentrations can also cause calcium, potassium, and magnesium deficiencies as the ammonium cation competes with other cations for plant absorption (Jones, 1998).

This explains why permeate adjusted to a lower pH experienced greater growth as nitric acid was used, thus increasing the concentration of nitrate ions within the solution.

Figure 29 Observed scorching of older leaves of tomato plants grown in pure AnMBR permeate solution (labeled P1). Such signs of stress are indicative of potassium deficiency/calcium toxicity.

These growth results agree with the results of multiple studies that concluded that low NO_3^-:NH_4^+ have a net negative effect on plant growth and yield (Borgognone, D. et al., 2013; Britto, D.T. & Kronzucker, H.J., 2002; Jones, J.B., 1998; Mortensen, L.M., 1987). Moreover, Borgognone, et al., (2013) observed that the effect of NH_4^+ nutrition in early growth stages was more pronounced than the effect of pH of the nutrient solution. Also, long term observation of NH_4^+ nutrition for tomato plants resulted in decreased plant growth and yield whereas the carbohydrate concentrations, amino acids, and proteins increased under NH_4^+ in comparison to NO_3^- nutrition (Borgognone, D. et al., 2013). The addition of nitrification stage to the process of permeate utilization could serve as a solution to the issue of high

NH_4/TN ratios exhibited by AnMBR Permeate. Such is seen in aquaponics systems where fish-waste rich in NH_4^+ is nitrified in plant beds filled with porous inert media.

Aquaponics systems operate in a fashion similar to the practice proposed by this experiment. Wastes from one process within a system serve as an input to another process within the system. The practice of aquaponics has experienced a lot of exposure recently as it conveys a more sustainable method of cultivating fish and crops for consumption. However, aquaponics systems still require inputs of a food source for the fish as well as make up water and energy to move water within the system (Bernstein, 2011). Similar systems that combine AnMBR technology for wastewater treatment with hydroponics systems can eliminate or replace the inputs of fish feed and makeup water. The AnMBR makes possible the safe extraction of nutrients from wastewater streams, effectively converting the outputs of human practices into inputs for the AnMBR-hydroponics system. Such integration represents a more sustainable option producing food crops.

Further investigation is necessary to legitimize the use of this form of treated effluent for household and commercial growing operations. Information regarding the presence of heavy metals, salinity, and nutrient composition for instance would prove beneficial. Also, if treated waste streams such as the AnMBR permeate used in this experiment are to be considered for fertilizer usage, a longer study is warranted to assess the yield capabilities and nutrient profile of food or other material crops that can be produced.

CHAPTER 5: FEASIBILITY ANALYSIS

Figure 30 Pilot scale system incorporating small scale decentralized wastewater treatment with various resource recovery capabilities. Greenhouse hydroponics system and algae photobioreactors are located adjacent to a structure housing an AnMBR system.

5.1 Introduction

The AnMBR technology makes possible the recovery of nutrients from a renewable supply of wastewater. A possible application for the nutrients recovered from an AnMBR system includes serving as the nutrient input for properly scaled hydroponics operations (Oyama, N.,Nair, J. & Ho, G.E., 2005). Utilizing nutrients recovered in AnMBR permeate can supplement or even replace the use of conventional nutrient fertilizers, one of the costs associated with hydroponics operations. The purpose of the feasibility analysis section is to analyze the social, economic, and environmental benefits associated with the recycling of nutrients for agricultural production made possible AnMBR technology.

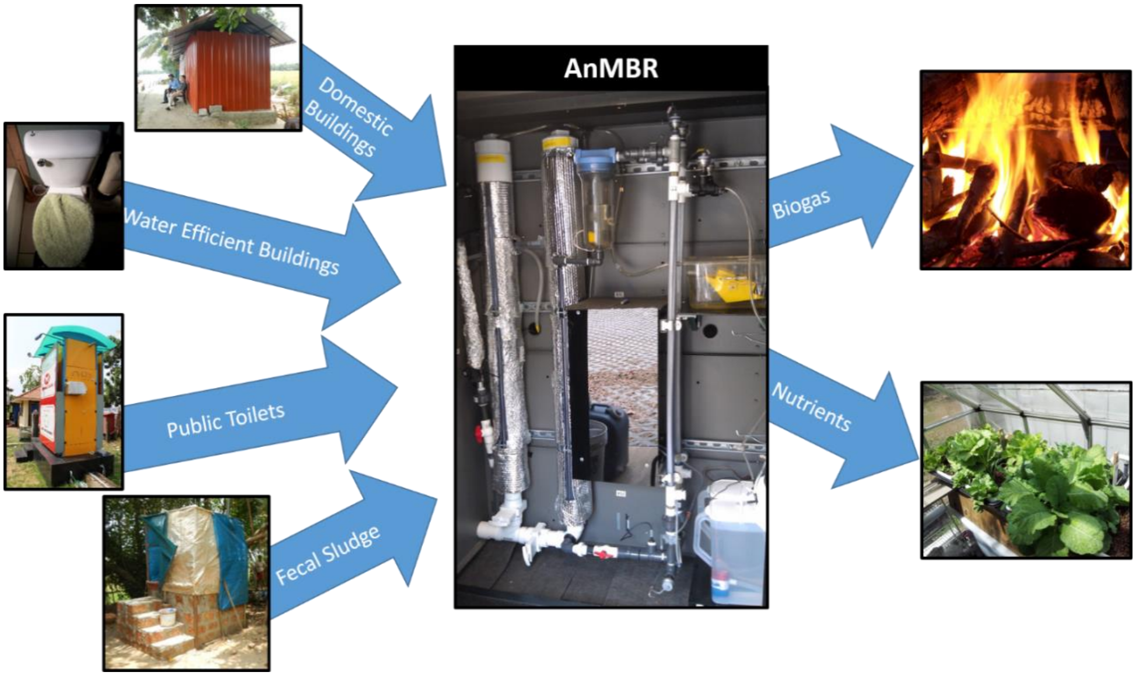

Figure 31 Potential applications of AnMBR systems in the developed and developing world

The concept of integrating hydroponic cultivation with the decentralized wastewater treatment capabilities of an AnMBR for enhancing food security in an urban setting inspired the work presented in this thesis. There are inherent synergies (Figure) associated with the integration of such systems that should be explored, exposed, and implemented. The recovery of nutrients, energy and water are all demonstrated by the performance of an AnMBR system (Li, A. et al., 1985; Norton-Brandão,Scherrenberg, S.M. & Van Lier, J.B., 2013; Smith, A.L., Stadler, L. B., Love, N. G., Skerlos, S. J., & Raskin, L., 2012; Smith, S.M., 2011). Efficient system design can take advantage of other synergies such as heat exchange from the combustion of biogas to regulate greenhouse temperature or heat nearby water supplies, as well as rerouting exhaust from biogas combustion to the greenhouse which raises CO_2 concentrations, thus enhancing growth (Epstein, E. & Bloom, A.J., 2005; Kimball, B.A., 1983; Wittwer, S.H. & Robb, W.M., 1964).

The integration of a decentralized wastewater treatment system with a hydroponics operation was realized on a small scale through the implementation of a pilot-stage AnMBR system at Learning Gate Elementary School in Lutz, FL (see Figure). A greenhouse was constructed adjacent to the AnMBR to house a hydroponics system that utilizes permeate created by the AnMBR, ultimately reusing the recovered nutrient resources. The resulting system serves as an example that visually conveys the implications of integrating decentralized wastewater treatment with agricultural applications. These implications include the possibility of the cohabitation of sanitation and agricultural operation with capabilities of off-the-grid operation, meaning the major input to an established system is wastewater. These characteristics make implementation of integrated decentralized wastewater treatment capable of resource recovery a viable tool for dealing with challenges associated with rapid urbanization in both developing and developed world contexts.

The model evaluates the proposed fate of nitrogen, phosphorous, and potassium (N, P, and K) post-AnMBR treatment. A previous model, developed by Onur Ozcan, approximates the performance of a small scale, decentralized AnMBR system treating human waste produced by a public toilet located in a coastal region of India. The AnMBR model approximates the amount of N, P, K and effluent leaving the system on a daily basis. The nitrogen, phosphorous, and potassium content, as well as the permeate flow rate is of particular interest to this study as this work intends to propose the integration of wastewater treatment with horticultural practices. This work serves to model the mass flow of N, P, K and water through a post-AnMBR hydroponic cultivation operation. Two AnMBR operation scenarios were modeled to compare their associated effects on post-AnMBR processes. The first scenario uses wastewater as the sole input to the AnMBR system and the effluent of that system serves as the influent to the post-treatment horticultural operations. A second scenario analyzes the performance associated with a mixed input of food waste (FW) and wastewater (WW). It is hypothesized that the additional organic content will increase nutrient content in the AnMBR effluent and thus yield a beneficial effect on post-treatment horticultural applications. The model for the proposed post-treatment processes depicts the effects of the co-digestion of FW and WW.

The digestion of food waste presents a possible opportunity for turning waste into a valuable resource. Globally, roughly a third of all food produced is wasted (Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., & Meybeck, A., 2011). In the U.S., food waste comprises 13.9% of the country's total waste stream("Municipal Solid Waste," 2013). Utilizing food waste for AD processes can enhance biogas production increasing the organic carbon content of the feed while reducing landfill usage and diverting greenhouse gas emissions associated with landfill usage (EPA, 2008; Rosso, D., and Stenstrom, M. K., 2008). The treatment and resource recovery capabilities of decentralized AnMBR systems can be employed for the treatment of food waste to provide renewable energy, recover nutrients for fertilizer applications, and to reduce the amount of organic wastes entering landfills.

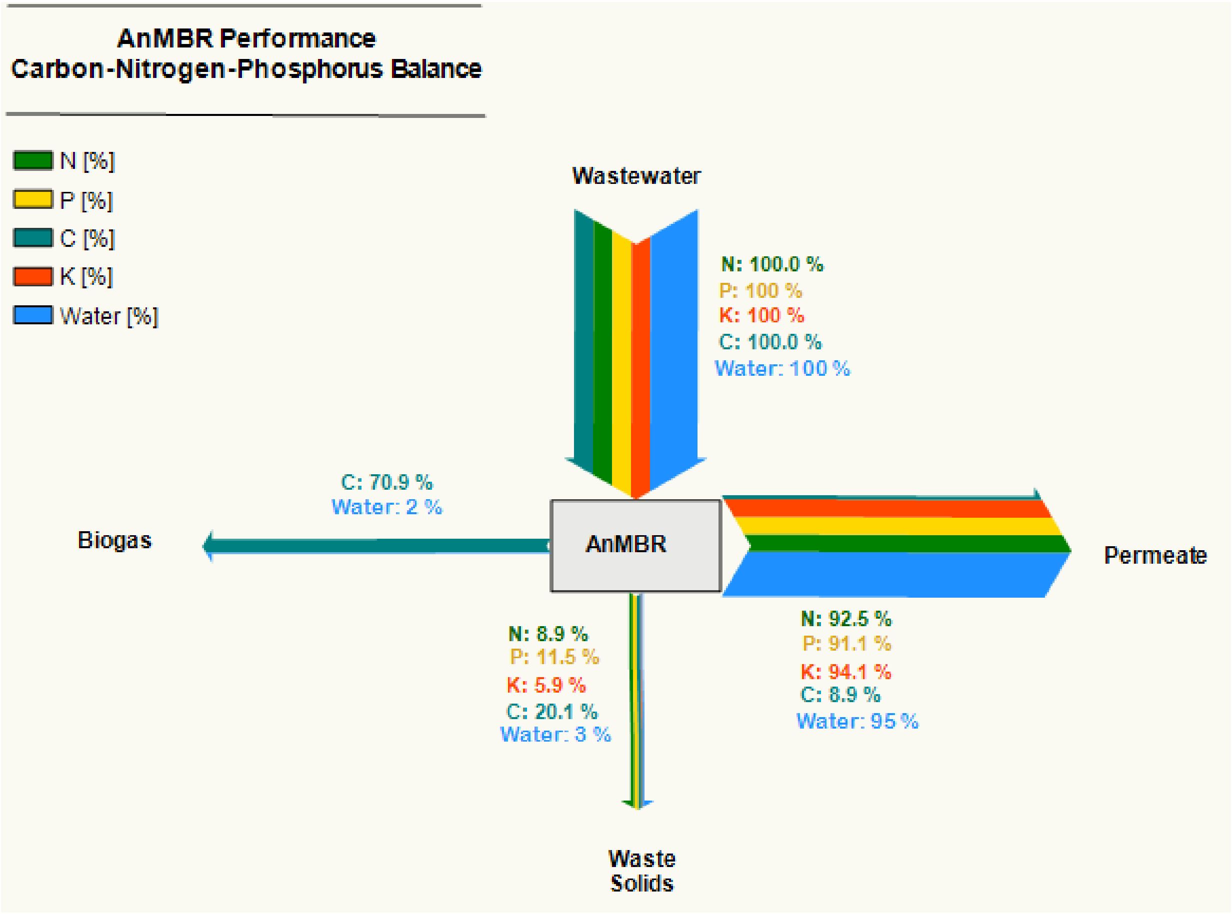

Figure 32 Fate of C, N, P, K, and water in the AnMBR System

Theoretical values for biogas production, nutrient recovery, and subsequent crop yields associated with AnMBR treatment of three waste streams were calculated by the model developed by a fellow PhD student, Onur Ozcan. Figure depicts the fate of nitrogen, phosphorus, and carbon bound in input waste material and their fates as they are processed by the AnMBR system. This study is mainly concerned with the utilization and optimization of the permeate stream. Future studies will aim to develop applications for the other two output stream of waste solids and biogas.

5.2 Model Development

The objective of the proposed post-treatment processes are first and foremost to utilize the maximum amount of N, P, and K within the permeate for the hydroponic production of value added crops, in this case, tomatoes were used due to the extensive amount of literature regarding tomato plant nutrient requirements and production. Post-treatment processes would then include necessary processes to capture excess nutrient content to ensure safe discharge and/or reuse. The model quantifies the amount of material utilized in each post-treatment process as well as process parameters.

The theme of this work is nutrient recovery and reuse, thus post treatment processes are chosen based on their ability to promote the utilization of nutrient content and while buttressing system stability. While hydroponic applications are a sink for dissolved nutrients, these applications require a specific balance of ionic nutrient species for optimal growth. The experiments performed in Chapter 4 indicate the need for conditioning AnMBR permeate prior to utilization for hydroponic fertigation.

The characteristics of the AnMBR feed indicate phosphorous as limited in the system, and contrarily, N and K appear to become highly concentrated in the effluent, thus warranting the need for reducing the amount of nitrogen and potassium prior to use within the hydroponic system. The model incorporates the nutrient removal capabilities of a constructed wetland consisting of Manchurian wild rice *(Zizania latifiolia*) in addition to a zeolite adsorption stage for the removal of ammonia-nitrogen.

Constructed wetlands represent another technology that utilizes the growth of biomass for nutrient removal. Constructed wetlands consisting of aquatic macrophytes such as the common reed, cat tails, wild rice, and duckweed have been utilized for treating anaerobic lagoon discharge often found in agricultural operations (Tanner, C.C., 1996). Plants used for constructed wetlands demonstrate high nutrient uptake capabilities, specifically N and K, which was shown to correlate with biomass production

(Tanner, C.C., 1996). Additionally, zeolites have long been used for removing ammonia from water via adsorption and ion-exchange phenomena (Hedstrom, A., 2001). A potential disadvantage associated with the use of zeolite for ammonium is that it presents additional costs to the overall system. This cost amplifies if an adequate regeneration process for spent zeolite is not established as the ammonia-enriched zeolite becomes an additional waste material and new zeolite will be required for further ammonia removal (Hedstrom, A., 2001). The addition of an ammonia removal process via zeolite fosters the potential for high nutrient removal capabilities. The following section states assumptions and the logic behind choosing them for the proposed system.

5.2.1 Assumptions

Several assumptions were made to facilitate calculations for the two AnMBR feed scenarios. Firstly, the design and operation characteristics of the AnMBR system are sized to serve the amount of wastewater and/or food waste produced from 100 events per day.

Productivity of the hydroponic stage was calculated assuming all environmental conditions for optimum growth (temperature, light, relative humidity, control from pests, etc.) were provided (Jensen, M.H. & Collins, W.L., 1985). Additionally, all essential micronutrients are assumed to be present in sufficient concentrations in addition to the macronutrients recovered by the AnMBR system. Hydroponic productivity was based on the amount of N, P, and K recovered. The number of plants able to be supported was calculated using the amount of available nutrients at a N:P:K ratio of 1:0.75:1.125 (Hochmuth, G.J. & Hanlon, E., 2000). Grow area was calculated using a land usage value of 4 sq. ft. per plant (Jensen, M.H. & Collins, W.L., 1985; Jones, J.B., 1998). Tomato yield per plant was estimated using a conservative value of 20 lbs. per plant per season (Hochmuth, R. & Toro, D., 2014). The theoretical revenue was calculated at a rate of $1.25 per pound of tomato (Hochmuth, R. & Toro, D., 2014). The estimated capital costs of the infrastructure necessary for the operation of nutrient film technique (NFT) hydroponics was calculated using a value of $81,000 per hectare (Jensen, M.H. & Collins, W.L., 1985) .

Phosphorous is assumed to be the limited nutrient component, thus the influent stream contains excess amounts of N and K. The constructed wetland consisting of *Zizania latifiolia* (ZL) is sized to uptake 5% of the remaining nitrogen content. 5% was chosen as an arbitrary value so as to decrease overall system size while minimizing the removal of nutrients to be utilized for hydroponic application. ZL is capable of removing nitrogen at a rate of 1.09 g N per m^2 per day, phosphorous at a rate of 0.15 g P per m^2 per day, and potassium at a rate of 1.64 g K per m^2 per day (Tanner, C.C., 1996). It is evident that AnMBR permeate contains prodigious amounts of ammonium warranting the need to reduce ammonium concentrations prior to use for fertigation. A zeolite adsorption process is used to adsorb excess ammonium that can be recovered outside the boundary of the proposed post treatment process. The removal of ammonia-N was assumed at a rate of 4.5 mg NH_4^- per gram of clinoptilolite. Zeolites also possess an ionic affinity for potassium higher than that of ammonium; however, the concentration of ammonium is far greater than that of potassium, thus favoring the increased removal of ammonium (Booker, N.A.,Cooney, E.L. & Priestly, A.J., 1996; Hedstrom, A., 2001; Kimochi, Y., Masada, T., Mikami, Y., Tsuneda, S., & Sudo, R., 2008; Parham, W.E., 1983).

The model calculations are based on values acquired from literature, yet in various contexts. The implementation of the proposed system warrants model design modification. This model is intended to demonstrate the nutrient resource recovery and utilization potential of a small scale decentralized wastewater treatment system

The AnMBR system characteristics were designed for the development of a low-impact decentralized system intended to meet the treatment demands of a public toilet that experiences 100 events per day. The composition of wastewater generated by the toilet was determined using usage statistics from (Jönson, H., Baky, A., Jeppsson, U., Hellström, D., & Kärrman, E., 2005). Wastewater flow rates were assumed from specifications provided by the public toilet manufacturer (ERAM Scientific Solutions Pvt. Ltd., Kerala, India).

A major advantage of co-digestion is the potential opportunity to turn abundant waste products into a source of energy while simultaneously reducing the net carbon footprint of the region by diverting carbon dioxide release from waste decomposition (Rosso, D., and Stenstrom, M. K., 2008). A daily flow rate of food waste was assumed to be 37.5 liters each day when diluted using a dilution factor of 1.5. These values represent arbitrary, yet conservative values.

Table 10 Composition of wastewater feed to AnMBR

Wastewater Feed Characterization		
Total Solids	2660	mg TS/L
Total Suspended Solids	1853	mg TSS/L
Total Dissolved Solids	807	mg TDS/L
Volatile Solids	1382	mg VS/L
Volatile Suspended Solids	838	mg VSS/L
Volatile Dissolved Solids	544	mg VDS/L
Total COD	2093	mg COD/L
Soluble Biodegradable COD	464	mg COD/L
Soluble Inert COD	39	mg COD/L
Particulate Biodegradable COD	1454	mg COD/L
Particulate Inert COD	136	mg COD/L
TN	392	mg TN/L
TP	51	mg TP/L
TK	114	mg TK/L

Table 11 Characterization of WW and FW co-digestion feed

Feed Characterization (Co-Digestion of WW and FW)		
Total Solids	16378	mg TS/L
Total Suspended Solids	1773	mg TSS/L
Total Dissolved Solids	14605	mg TDS/L
Volatile Solids	1498	mg VS/L
Volatile Suspended Solids	113	mg VSS/L
Volatile Dissolved Solids	1385	mg VDS/L
Total COD	22087	mg COD/L
Soluble Biodegradable COD	37842	mg COD/L
Soluble Inert COD	5962	mg COD/L
Particulate Biodegradable COD	28707	mg COD/L
Particulate Inert COD	2384	mg COD/L
TN	509	mg TN/L
TP	57	mg TP/L
TK	132	mg TK/L

5.3 Analysis Results

Table 12 Results of the theoretical integration model.

	Wastewater Treatment	units	FW Co-Digestion	
Nitrogen	297	g/day	473	g/day
Phosphorus	38	g/day	64	g/day
Potassium	87	g/day	153	g/day
Min. Grow Area Required	1715	sq. ft.	2939	sq. ft.
Theoretical Tomato Yield	8,661.35	lbs./season	14,842.59	lbs./season
Agricultural Revenue	$10,826.69	per season	$18,553.24	per season
Hydro. System Cost (NFT)	$2,581.05		$4,423.03	
Methane Produced	373.05	g CH4/d	3,034.86	g CH4/d
Biogas Energy Content	5.5	kWh/d	44.5	kWh/d

Results of the feasibility analysis indicate that the co-digestion scenario yields the best potential to produce biogas and value-added products in the form of tomatoes grown from nutrients recovered by the AnMBR system. The high organic carbon content of food waste promotes biogas production and can tolerate a higher OLR ($16\ g\ l^{-1}\ d^{-1}$). Wastewater is diluted by a number of washing practices which lowers the COD concentration while nutrient concentrations can remain relatively high. The co-digestion scenario yielded a methane production much higher than treating solely wastewater due to the increased organic load.

The results indicate that there are clear advantages associated with the co-digestion of food waste and wastewater in regards to methane production and nutrient recovery. Further research is necessary to determine the validity of the hydroponics production model as yield values were based on optimal growing conditions.

The fates of materials leaving the AnMBR treatment process in both scenarios are depicted in the Sankey diagrams below. The figures provide visual representation for mass balances of nitrogen, phosphorous and potassium in post treatment processes.

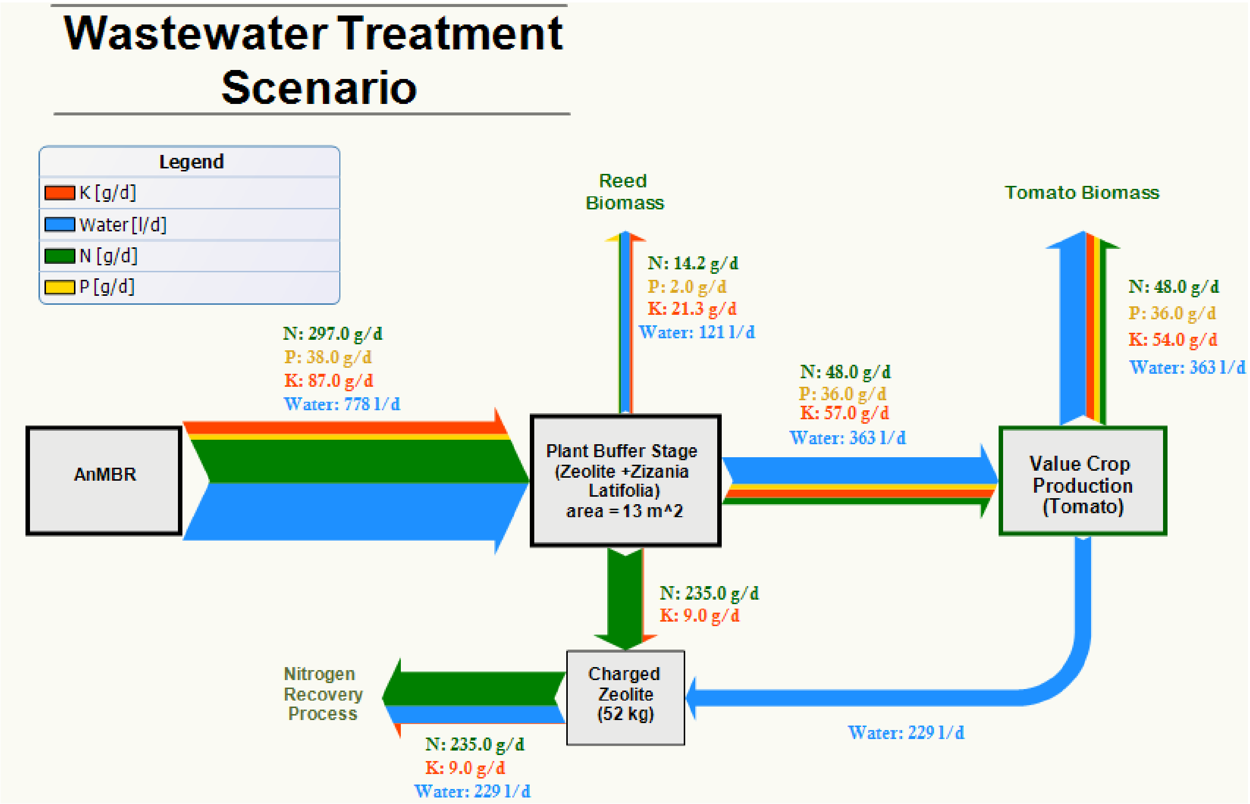

Figure 33 Daily mass flows of nutrients recovered by an AnMBR treating typical wastewater generated by a public toilet.

When under ideal conditions, the proposed post treatment processes remove all phosphorous via synthesis to biomass, both value added product biomass and buffer zone plant biomass. Excess potassium can be kept as a background nutrient and may even enhance tomato yield (Hochmuth, G.J. & Hanlon, E., 2000). However, the ion exchange processes facilitated by the zeolite will most likely remove the excess potassium

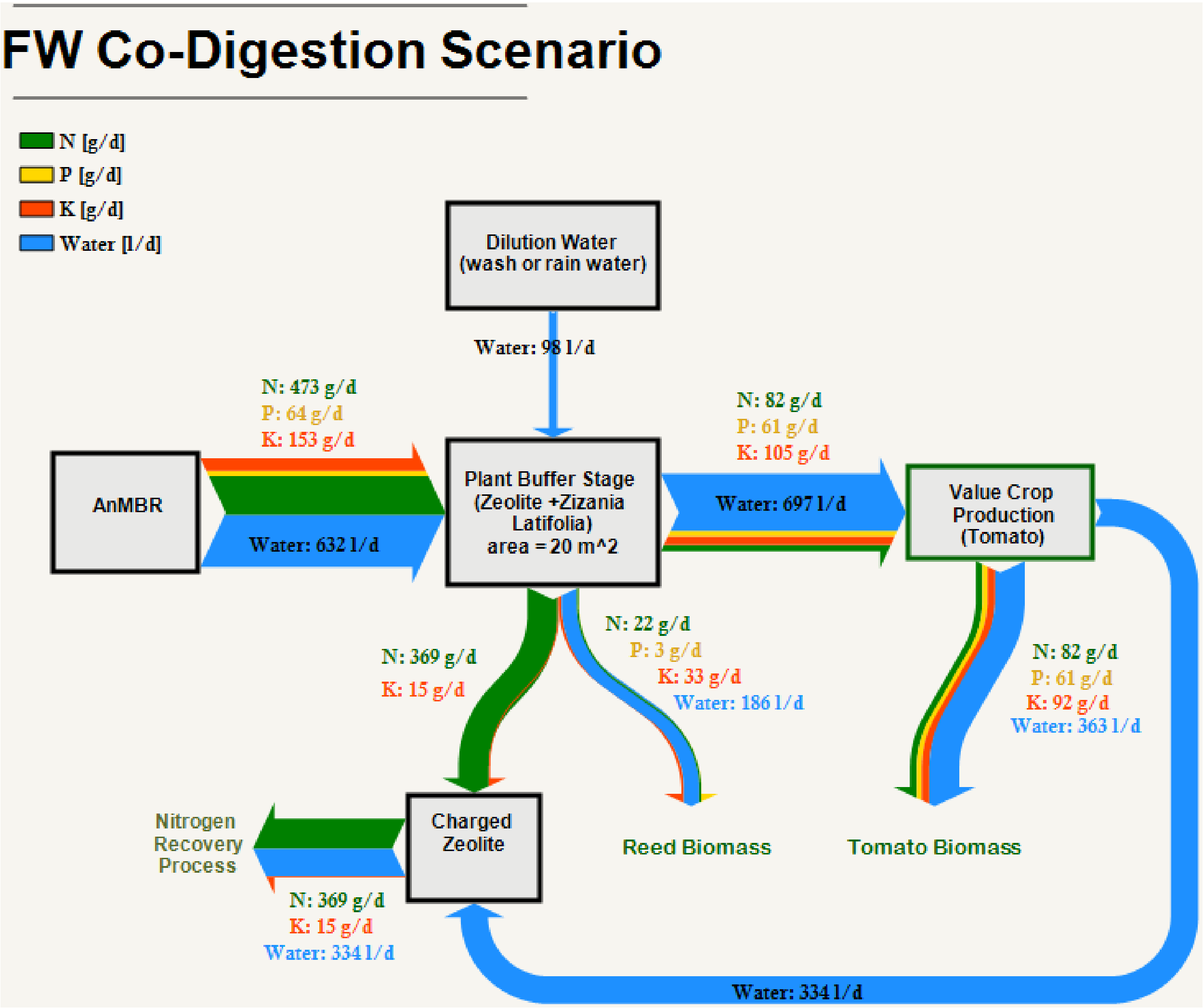

Figure 34 Daily mass flows of nutrients recovered from the co-digestion of wastewater and food waste via AnMBR treatment.

5.4 Discussion

Based off the results provided in Table 12, there exists an estimated potential to generate revenue. These values are preliminary, but due to the fact that hydroponic cultivation can experience high yields in smaller areas, the hydroponic area that can be sustained from nutrients within permeate can potentially make small areas more productive.

A buffer stage was implemented to *condition* the permeate to a more hospitable state prior to utilization within the hydroponics stage (termed value crop production in the figures above). Ideally, this stage would consist of plant species that tolerate a wide range of nutrient concentrations. For this model, Manchurian wild rice (*Zizania latifiolia*) was chosen for its high nitrogen and potassium uptake rates and low phosphorus uptake rate (Tanner, C.C., 1996). An added benefit of the buffer stage is that it allows for additional utilization of excess N and K into the biomass of the *Zizania latifiolia* (ZL) while allowing for the maximum amount of the limiting nutrient P to pass to the value crop production stage. Biomass produced in the buffer stage must be harvested in order to remove the nutrients from the system boundary. Harvested ZL biomass can be used for livestock feed applications(Tanner, C.C., 1996).

In addition to the buffer stage, a zeolite adsorption/ion exchange stage is needed to remove the excess ammonium. Zeolitic materials require regeneration of the ion exchange sites once they have been occupied by exchanged ions. A typical method for regenerating zeolite involves flushing the ammonium-enriched zeolite with highly concentrated sodium solutions to promote the exchange of NH_4^+ with Na^+. This effectively and rapidly regenerates the zeolite material but the ammonium content that is removed is now contained in an extremely brackish solution that is typically not suitable for reuse. The zeolite regeneration process is outside the boundary of the system proposed. Ideally, a regeneration process that utilizes captured nitrogen content while recovering zeolite material for further use would complement the proposed system. Recovering regenerated zeolite is a design goal so as to reduce the amount of consumable materials employed in the proposed system.

In the post treatment process following AnMBR treatment of FW co-digested with WW, dilution water was needed in order to achieve hospitable nutrient concentrations in the plant growth stages. The volume of dilution water was determined by the amount of additional water needed to achieve a nitrogen concentration of 150 mg N/l entering the tomato growth stage (Hochmuth, G.J. & Hanlon, E., 2000). 98 liters per day was calculated as the dilution water requirement. Ideally this requirement would be met with greywater or captured rain water to reduce costs.

CHAPTER 6: CONCLUSION

6.1 Conclusions

This work has observed the performance of permeate when utilized as a nutrient source for hydroponic applications. Additionally, a model was created to assess the potential benefits achieved by resources recovered from a theoretical system that integrates the AnMBR technology with hydroponic grow operations. Major conclusions of this work are:

- Integration of decentralized wastewater treatment systems with food production operation is feasible through the utilization of AnMBR and hydroponics systems
- Permeate generated by a pilot scale AnMBR was able to successfully grow tomato plants, however nutritional insufficiencies reduced growth.
- Co-digestion of wastewater and food waste presents the best opportunity for recovering energy and nutrients while supplementing water use for agricultural activities.
- A hydroponics operation optimized for use of AnMBR permeates shows potential to produce value added products from recovered nutrients.
- The proposed system demonstrates high applicability in urban settings by demonstrating a low system footprint and decentralized resource recovery
- Ammonium is the dominant form of nitrogen in AnMBR permeates which reduces its suitability as a direct nutrient source. A conditioning stage is necessary prior to utilization in a hydroponics system
- AnMBR permeate contains excess nitrogen and limited phosphorous, thus warrants the need for removal the excess nitrogen to reduce environmental damage.

6.2 Future Research

Future research should serve to improve upon and legitimize the sustainability of the integrated system proposed in this work. The social, economic, and environmental implications of incorporating integrated system technologies, such as the system proposed, must be identified and addressed. Social sustainability can be enhanced by decreasing the cost and complexity of the system and also by facilitating stakeholder ownership. Economic sustainability can be improved by optimizing the performance of an integrated AnMBR-hydroponics system for maximum biogas generation, and maximum plant growth and yields. Biogas generation will serve to offset the costs of operation by reducing, replacing, or even producing excess power. Environmental sustainability is enhanced by reducing nitrogen fertilizer production, non-renewable resource consumption, and by the preservation of arable land that would have otherwise been utilized for unsustainable agricultural practices (Maheshwari, B. et al., 2014).

Future research is necessary in order to optimize the composition of permeate obtained from AnMBR technologies for applications in hydroponics and/or any other type of controlled environment agriculture (CEA) (Jensen, M.H. & Collins, W.L., 1985). The hydroponics growth experiments concluded that permeate collected from the pilot AnMBR system was unfit for achieving maximum growth and yield of tomato plants when used as is. Future research can serve to determine cost-effective, permeate post-treatment and/or conditioning processes necessary to yield permeate of high quality nutrient value for hydroponics applications. Cost effectiveness is essential so as to not nullify the economic advantages of recovering nutrients as opposed to purchasing fertilizers.

Additionally, the model developed in chapter 5 predicted an excess amount of nitrogen would be generated by the AnMBR and would require removal. The nitrogen within AnMBR permeate is predominantly in the form of NH_4^+. Ammonium can be removed from aqueous solutions via chemical/precipitation, volatilization, ion exchange, or even biological methods. Regeneration via ion exchange with sodium was discussed earlier. Past studies have experienced success removing ammonia by first raising pH followed by air stripping. Raising the pH of an aqueous solution past 9.3 (the pKa of

NH_4^+/NH_3) converts ammonium to ammonia which readily volatilizes from solution. This method requires chemical input to raise the pH and also to capture volatilized ammonia (Tchobanoglous, G. et al., 2014).

Many large scale wastewater treatment facilities utilize biological nutrient removal performed by nitrifying and denitrifying bacteria. Ammonium is oxidized by nitrifying bacteria, first to nitrite (NO_2^-), then to nitrate (NO_3^-) (Tchobanoglous, G.,Burton, F.L. & Stensel, H.D., 2003). Biological regeneration of zeolite can be accomplished by impregnating the zeolite reactor with colonies of nitrifying bacteria and supplying the bacteria with adequate aeration to perform nitrification (Hedstrom, A., 2001). After nitrification, nitrogen has only been transformed to the oxidized form of nitrate which still poses environmental risk which is why regulatory agencies require extremely low N discharge concentrations (EPA, 2012). Nitrate is removed in the process of denitrification which occurs in anoxic environments. In anoxic environments, denitrifying bacteria utilize nitrate as an electron acceptor during respiration, reducing nitrate to N_2 gas in the process. The newly formed molecular nitrogen (N_2) then volatilizes from solution into the atmosphere (Tchobanoglous, G. et al., 2003). Disadvantages associated with biological nitrogen removal (BNR) are the needs for aeration to perform nitrification, and often an organic carbon source is necessary for denitrification. Additionally, this process removes nitrogen and the design goal of this work is to recover nutrients for useful applications.

Future work will investigate the applicability of nitrifying ammonia-enriched zeolite within a hydroponic grow bed. Nitrate produced by nitrification can then be delivered to plant roots by the mechanisms of root-interception and/or diffusion into solution. Ideally, this configuration would represent a cyclical process of continuous ammonia-enrichment and biological regeneration via nitrification and plant uptake.

Remote location is a characteristic that favors the implementation of decentralized systems. To better facilitate the management of decentralized AnMBR and hydroponics systems, system automation is a design imperative. AnMBR systems have a high capacity for automation (Stephenson, T. et al., 2000) as do hydroponics systems (Jensen, M.H. & Collins, W.L., 1985). Future research should be conducted to streamline the integration of these two systems. Remote, real time control capabilities are an introductory step towards automation. Advanced automation measures for AnMBR systems should incorporate native response mechanisms that can adjust reactor operation parameters for maximum treatment and resource recovery efficiency. The same ideology for automation mechanisms would apply to the adjacent hydroponics system. Enhancing the automation characteristics of these systems would enhance their applicability in a wider range of environments as the demand for highly trained operators is reduced, if not eliminated.

Important consideration when discussing the reuse potential of AnMBR permeate are the public health risks associated with reuse applications. This work proposes reuse scenarios where AnMBR permeate is treated to a quality fit for reuse in horticultural applications. Non-edible plant production applications present an option that would reduce the potential for risking public health. However, to address issues of food security, edible crop production might possibly become a consideration for which the safety of such use must be addressed. Future studies should serve to address concerns specific to the use of permeate for edible crop production, to investigate pathogen reduction and removal throughout the AnMBR process as well as the uptake rate of plants in a hydroponics system. One study measured the removal of virus-sized bacteriophages in an AnMBR system with a membrane pore size of 0.4 µm. The study observed up to 5.5 log removal of MS-2 bacteriophages of a diameter of 25 nm. Phage removal was observed to be enhanced with addition of anaerobic biomass and increasing gas sparging rates (Fox, R.A. & Stuckey, D.C., 2014)

Regardless, implementation of the integrated system proposed poses several implications for improving urban communities by generating useable resources in the form of biogas and nutrients. Biogas can be used to fuel or power local business while the nutrient rich permeate can be utilized for fertigation of aesthetic landscapes or for the hydroponic production of useful crops. Social acceptance may hinder the use of permeate for the production of crops that are intended for human consumption, in which case permeate can be utilized to produce other useful fiber crops or feed crops for livestock or aquaculture production. Either way, wastewater remains to be a valuable, renewable source of resources that AnMBR technology can tap into.

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APPENDICES

Appendix A Mass Balance Excel Model

Table A1 Excel sheet for nutrient modeling in the wastewater-only scenario

Hydroponics production: Wastewater Scenario		
methane generated	373	g/day
marketable tomato yield	5,109.62	g tomato/sq. ft./yr.
Tomato plant nitrogen use	110.00	mg/plant/day
Hydroponic tomato space requirement	0.25	plants/sq. ft.
Plants that can be grown	433.07	plants
Hydro system space req'd	1,714.95	sq. ft.
Yield enhanced with CO2 at	33.00	% increase
CO2 required for enhanced growth	1,000.00	ppm
Captured CO2 from oxidized methane	1,025.90	g CO2/d
Required CO2 flow rate	278.71	g/sq. ft./hr.
CO2 flow rate	0.02	g CO2/h/sq. ft.
% enhancement factor from CO2 added	0.00	
theoretical marketable tomato yield	8,762,979.99	g tomato/yr.
price per pound	$1.25	$/lb.
Theoretical Revenue	$24,148.85	$/yr.
area	0.015932397	ha
	$1,515,707.23	$/ha
grow area with 1000 ppm CO2	4.528662291	sq. ft. (ht. = 8 ft.)
Nitrogen used for Fertilizer	48	g N/day
Phosphorus Used for Fertilizer	36	N:P
Potassium used for Fertilizer	54	N:K
amount of complete fertilizer (1-0.75-1.125)	47637.425	mg **N**:P:K/day
Plants that can be grown	**433**	**plants**
Space required	**1714.9473**	**sq. ft.**
Marketable yield	8762721.385	g/yr.
Theoretical Revenue	$19,318.51	$/yr.
Tomato yield per plant	20	lb. / plant
Excess Nitrogen	**0**	g/d
Excess Phosphorus	**0**	g/d
Excess Potassium	**13**	g/d
Tomato Yield	**8,661.35**	lbs./season
Theoretical Revenue	**$10,826.69**	per season
Reed N removal Rate	1.090	g/m2/day
Reed P removal Rate	0.150	g/m2/day

Table A1 (Continued)

Reed K Removal Rate	1.640	g/m2/day
Buffer Stage Area	**13.00**	**m2**
Buffer N-removal	14.17	g/day
Buffer P-removal	1.95	g/day
Buffer K-removal	21.32	g/day
WATER flow leaving AnMBR	**778.08**	l/d
Tomato Water uptake rate	25.00	g/l
Tomato Water uptake	**363**	liters/day
Buffer Evapotranspiration rate	9303	ml/m2/day
Buffer zone water loss	**121**	liters/day
[N] incoming to Buffer stage	79	mg/l
[P] Incoming to Buffer stage	48	mg/l
[K] incoming to Buffer stage	101	mg/l
[N] incoming to Crop stage	72	mg/l
[P] Incoming to Crop stage	54	mg/l
[K] incoming to Crop stage	87	mg/l
zeolite removal column	4.5	mg NH-4/g
recommended [N]	150	mg/l
dilution water need	**0**	liters
Zeolite needed to remove 79% N	52275	g zeolite
NH4-N Removed	235	g/day
Density of Clinoptilolite	-	-
Volume of Zeolite Adsorption Column	-	-
Zeolite Potassium Removal	8.74665	g/day
Diluted [N] to tomato production	72.4915891	mg/L
Cost of Zeolite (clinoptilolite)	$130	1000 kg
Zeolite costs	$6.80	day

Table A2 Excel sheet for nutrient modeling in the co-digestion scenario

Hydroponics production		
methane generated	3035	g/day
marketable tomato yield	5,109.62	g tomato/sq. ft./yr.
Tomato plant nitrogen use	110.00	mg/plant/day
Hydroponic tomato space requirement	0.25	plants/sq. ft.
Plants that can be grown	742	plants
Hydro system space req'd	2,938.83	sq. ft.
Yield enhanced with CO2 at	33.00	% increase
CO2 required for enhanced growth	1,000.00	ppm
Captured CO2 from oxidized methane	8,345.87	g CO2/d
Required CO2 flow rate	278.71	g/sq. ft./hr.
CO2 flow rate	9.44	g CO2/h/sq. ft.
% enhancement factor from CO2 added	0.01	
theoretical marketable tomato yield	15,184,132.13	g tomato/yr.
price per pound	$1.25	$/lb.
Theoretical Revenue	$41,844.14	$/yr.
area	0.027302684	ha
	$1,532,601.54	$/ha
grow area with 1000 ppm CO2	36.84141325	sq. ft. (ht. = 8 ft.)
Nitrogen used for Fertilizer	**81.63**	g N/day
Phosphorus Used for Fertilizer	**61.23**	N:P
Potassium used for Fertilizer	**91.84**	N:K
amount of complete fertilizer (1-0.75-1.125)	**81634.26667**	**mg N:P:K/day**
Plants that can be grown	**742**	**plants**
Space required	**2938.8336**	sq. ft.
Marketable yield	15016309.85	g/yr.
Theoretical Revenue	$33,105.32	$/yr.
Tomato yield per plant	20	lb. / plant
Excess Nitrogen	**0**	g/d
Excess Phosphorus	**0.000**	g/d
Excess Potassium	**29**	g/d
Tomato Yield	**14,842.59**	lbs./season
Theoretical Revenue	**$18,553.24**	per season
Reed N removal Rate	1.090	g/m2/day
Reed P removal Rate	0.150	g/m2/day
Reed K Removal Rate	1.640	g/m2/day
Buffer Stage Area	**20.00**	**m2**
Buffer N-removal	21.80	g/day

Table A2 (Continued)

Buffer P-removal	3.00	g/day
Buffer K-removal	32.80	g/day
WATER flow leaving AnMBR	**632.26**	l/d
Tomato Water uptake rate	25.00	l/g
Tomato Water uptake	**362.87**	liters/day
Buffer Evapotranspiration rate	9303	ml/m2/day
Buffer zone water loss	**186.06**	liters/day
[N] incoming to Buffer stage	164	mg/l
[P] Incoming to Buffer stage	102	mg/l
[K] incoming to Buffer stage	218	mg/l
[N] incoming to Crop stage	183	mg/l
[P] Incoming to Crop stage	137	mg/l
[K] incoming to Crop stage	236	mg/l
zeolite removal column	4.5	mg NH-4/g
recommended [N]	150	mg/l
dilution water need	**98**	liters
Zeolite needed to remove 78% N	**82022**	g zeolite
NH4-N Removed	**369.1004833**	g/day
Density of Clinoptilolite		
Volume of Zeolite Adsorption Column		
Zeolite Potassium Removal	15.33015	g/day
Diluted [N] to tomato production	150	mg/L
Cost of Zeolite (clinoptilolite)	$130	1000 kg
Zeolite costs	$10.66	day

Appendix B Continued Greenhouse Growth

The greenhouse location experienced continued operation without experimentation or measurement. Originally constructed with the intention of housing a small aquaponics operation, the greenhouse located at Learning Gate Elementary school in Lutz, FL utilized AnMBR permeate generated by and adjacently located AnMBR system that was treating wastewater from the school's septic tank. The permeate that was generated was diluted with rain water captured on site and utilized in the aquaponics system. The system contained no fish, thus the ammonia content in the permeate served as the input nitrogen. Various plants were grown in four, 20 liter grow beds filled with hydroton including basil, tomatoes, rosemary, and Moringa Oleifera. Addition of permeate to the hydroponics system was infrequent, yet tomato plants growing in the system displayed dense vegetative growth and vigor.

Figure B1 Diluted AnMBR permeate can support extensive vegetative growth

Figure B2 The greenhouse system using AnMBR permeate generated onsite yielded many tomatoes

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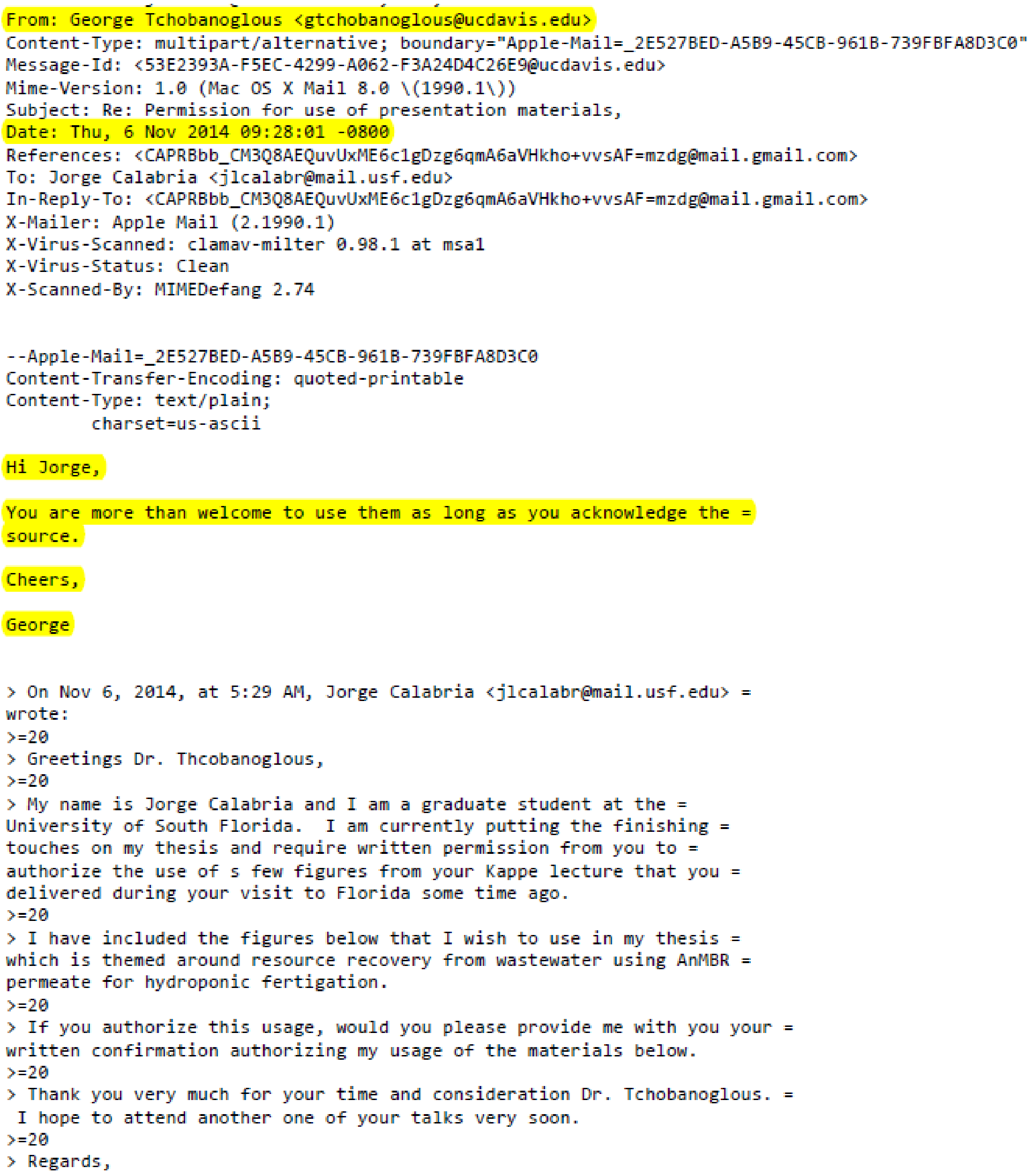

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From: George Tchobanoglous <gtchobanoglous@ucdavis.edu>
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Hi Jorge,

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source.

Cheers,

George


> On Nov 6, 2014, at 5:29 AM, Jorge Calabria <jlcalabr@mail.usf.edu> =
wrote:
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> Greetings Dr. Thcobanoglous,
>=20
> My name is Jorge Calabria and I am a graduate student at the =
University of South Florida.  I am currently putting the finishing =
touches on my thesis and require written permission from you to =
authorize the use of s few figures from your Kappe lecture that you =
delivered during your visit to Florida some time ago.
>=20
> I have included the figures below that I wish to use in my thesis =
which is themed around resource recovery from wastewater using AnMBR =
permeate for hydroponic fertigation.
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> Thank you very much for your time and consideration Dr. Tchobanoglous. =
 I hope to attend another one of your talks very soon.
>=20
> Regards,
```

ABOUT THE AUTHOR

Jorge Calabria received his Bachelor of Science degree in Civil and Environmental Engineering from the University of South Florida. Jorge is genuinely passionate about plants and their capabilities to improve the human condition by sequestering carbon, cleaning water, and providing nourishment. He hopes to merge his passion for plants with his academic endeavors to develop improved sanitation technologies that turn wastes into resources. Jorge's academic and personal endeavors strive to change the way society views waste by promoting it as an untapped resource. Jorge actively participates in educational outreach programs facilitated by Dr. Yeh's lab group that aim to expose young people to concepts of elemental "biorecyling" and the role it plays in converting perceived wastes into valuable resources.

In addition to continuing his research focused on securing sustainability, Jorge is fond of the outdoor lifestyle and is an active member of The Rock Climbing Club at USF which he founded in 2007 and has since served as president.