I, Daniel Scott, hereby submit this original work as part of the requirements for the degree of Master of Science in Environmental Engineering.

It is entitled:
Biological Nitrogen Removal in a Gravity Flow Biomass Concentrator Reactor

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Biological Nitrogen Removal in a Gravity Flow Biomass Concentrator Reactor

A thesis submitted to the
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Prepared by

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B.S. Civil Engineering
University of Utah, 2009

Committee Chair:
Dr. Makram Suidan, Ph.D.
Abstract

Membrane technology is a well established method for wastewater treatment with advantages including: relatively easy to operate; low turbidity and BOD in the effluent; and less space required for treatment (Tchobanoglous et al., 2003). However, some of these benefits are offset by a few disadvantages including: higher capital cost; high energy costs; and high maintenance costs (Tchobanoglous et al., 2003). A novel gravity-flow filtration system named a Biomass Concentrator Reactor (BCR), developed by EPA-NRMRL and the University of Cincinnati (Patent No. 6821425 issued Nov. 23, 2004), has been proposed to achieve lower cost membrane filtration while maintaining the benefits of typical membrane bioreactors.

The BCR was tested using synthetic municipal wastewater under conditions of typical aerobic degradation, as well as alternating aerobic and anoxic conditions for biological nitrogen removal. Two solids retention times (SRT) were considered, 6 day and 15 day, at 9 hour hydraulic retention time (HRT). The recycle flow for the alternating aerobic/anoxic reactor was twice the reactor flow rate.

Under these conditions, the BCR was able to achieve nearly 100% solids separation of mixed liquor with less than 2.5 cm of hydraulic head loss. Total nitrogen (TN) and chemical oxygen demand (COD) removals are summarized in the table below for the various operating conditions. Reactor 1 was operated with separate aerobic and anoxic sections while reactor 2 was operated under only aerobic conditions.

<table>
<thead>
<tr>
<th></th>
<th>HRT (hrs)</th>
<th>SRT (days)</th>
<th>COD removal (%)</th>
<th>TN removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor 1</td>
<td>9</td>
<td>6</td>
<td>95</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>97</td>
<td>75</td>
</tr>
<tr>
<td>Reactor 2</td>
<td>9</td>
<td>6</td>
<td>93</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>93</td>
<td>43</td>
</tr>
</tbody>
</table>
Acknowledgement

I am first and foremost grateful to my advisor, Dr. Makram Suidan, for all of his support as well as my committee, Dr. Sorial and Dr. Venosa. To my associates within the project, Dr. Pablo Campo and Dr. Taira Hidaka, thanks for everything. Thanks as well to all the students in our research group. And finally, to my wife Jen who has been with me now through 6 years of higher education, I could never have done it without you.
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1. Introduction

Membrane Biological Reactors (MBRs) have been widely accepted as a feasible alternative to conventional wastewater treatment due to its smaller overall footprint and relative ease of operation (Tchobanoglous, Burton, & Stensel, 2003). However, several downsides including high pressure operation and membrane fouling have prevented the technology from becoming more widespread (Tchobanoglous et al., 2003). Research in this area has lead to the development of a gravity-flow Biomass Concentrator Reactor (BCR) by EPA-NRMRL and the University of Cincinnati (Patent No. 6821425 issued Nov. 23, 2004). Under low pressure, a pilot scale reactor utilizing a BCR showed good removal in aerobic biodegradation of methyl tert-butyl ether (MTBE) at a concentration of 5 mg/L (Zein, Suidan,& Venosa, 2004).

Nutrient removal is increasingly becoming an important issue at the forefront of wastewater treatment because of the devastating impact nutrients can have on receiving bodies of water (Nazaroff & Alvarez-Cohen, 2001). Biological nutrient removal (BNR) offers a cost effective and sustainable way of removing nutrients from waste streams (Tchobanoglous et al., 2003). Several methods and designs have been developed to accomplish nitrogen and/or phosphorus removal and the technology is widespread, with some full scale facilities utilizing the technology (Tchobanoglous et al., 2003).

In order to address these growing needs in the field of wastewater treatment, research has been conducted on the previously developed BCR system in order to understand its applicability in municipal wastewater treatment and its effectiveness in achieving biological nitrogen removal.
2. Background

2.1 Biological Nutrient Removal

Excessive nutrients in aquatic ecosystems, including nitrogen and phosphorus, lead to increased microbial and algae growth resulting in ecosystem imbalance which can threaten natural aquatic life (Nazaroff & Alvarez-Cohen, 2001). Wastewater is one significant source of excess nutrients in aquatic systems. This has lead to increased regulation as well as innovation of various technologies for control.

Biological nutrient removal (BNR) has become widely adopted as an inexpensive and reliable way of removing nitrogen and phosphorus from wastewater (Tchobanoglous et al., 2003). Nitrogen is removed biologically by a process known as denitrification, where, under conditions of limited oxygen, certain microorganisms utilize nitrite and nitrate as electron acceptors in their metabolism and generating nitrogen gas as the nitrogen containing product (Tchobanoglous et al., 2003). Several reactor types exist that can perform biological nitrogen removal, but most utilize two stages, an aerobic and anoxic, with recycling in between zones (Tchobanoglous et al., 2003). In the aerobic section, ammonia and organic nitrogen are converted to nitrate, fluid containing nitrate is then recycled to the anoxic section where the nitrate is converted to nitrite, then nitrogen gas by way of denitrification (Tchobanoglous et al., 2003).
One reason BNR has been so widely accepted is because of the relative ease of implementation in existing WWTPs (Randall et al., 1992). In many cases, by modifying the flow patterns, mixing conditions, aeration, and other variables, existing WWTPs can use the structures that are already on site to achieve nitrogen removal without the need for added infrastructure (Randall et al., 1992). Advantages to including BNR in a WWTP besides nitrogen removal include: less aeration is required; less biosolids are produced, and reduction or elimination of bulking problems (Randall et al., 1992).

Computerized optimization techniques have proved to be worthwhile in increasing nitrogen removal as well as reducing aeration requirements. Study of the effects of internal recycle on anaerobic/anoxic/oxic WWTP by Baeza et al., (2004) showed an increase in 12% nitrogen removal by increasing the internal recycle ratio to 5. Using a bioprocess intelligent optimization system (BIOS) to control aeration and internal recirculation, a 36% increase in nitrogen removal and 19% decrease in aeration was achieved for a modified Ludzack-Ettinger treatment process (Liu et al., 2005).

2.2 Membrane Biological Reactors

Membrane filtration is a process used to separate particulate material from a liquid. Unlike traditional filtration however, membranes are able to remove very small particles sometimes as low as 0.0001 µm in diameter (Tchobanoglous et al., 2003). Membranes are classified based on the nominal size of the separation achieved, as well as by material, driving force, and separation mechanism (Tchobanoglous et al., 2003).
wastewater treatment, the typical pore size is 0.1 to 0.4 µm which falls under the category of microfiltration, by which the driving force is hydrostatic pressure difference and the dominant separation mechanism is by sieve (Tchobanoglous et al., 2003).

Membrane filters in wastewater treatment can be used in several different ways, but are most commonly used in what are known as membrane biological reactors (MBR) in which the membrane is either placed directly inside the biological reactor or the mixed liquor is pumped under pressure the an external membrane (Mallevialle et al., 1996). The membrane separates the solids from the liquid which is then sent directly to tertiary treatment or disinfection eliminating the need for secondary clarification (Mallevialle et al., 1996). Strong aeration is typically provided to achieve supply of dissolved oxygen (DO) for COD removal and nitrification, complete mixing, and scouring of the exterior of the membrane. A pressure differential between the retentate and permeate must be applied in order for the desired flow rate to pass through the membrane (Tchobanoglous et al., 2003). As this process proceeds, clogging or fouling of the membrane pores force either an increase in pressure differential, or decrease in flow-rate (Tchobanoglous et al., 2003). At a certain point, it is cost prohibitive to continue using the membrane and it must either be regenerated or replaced.

Because MBRs have no need for secondary clarification, the bioreactors are typically maintained at a higher mixed liquor suspended solids (MLSS) concentration creating several advantages to traditional treatment including: higher volumetric loading rates and thus shorter hydraulic retention times; longer solids retention time (SRT) or
sludge age resulting in less sludge production; lower turbidity and BOD in the effluent; and less space required for treatment (Tchobanoglous et al., 2003). However, some of these benefits are offset by a few disadvantages including: higher capital cost; high energy costs; and high maintenance costs (Tchobanoglous et al., 2003).

Many variations on the typical MBR system have been tested in an effort to maintain the advantages of an MBR (effluent quality, ease of operation, and compact footprint) while diminishing the disadvantages (high capital, energy, and maintenance costs). One such variation called an immersed membrane activated sludge system by Cote et al. (1997) was operated on a pilot scale and showed excellent effluent quality while producing 50% less sludge than a conventional activated sludge plant and used only 0.3 kWh/m$^3$ of energy for filtration.

2.3 Nitrogen Removal in MBRs

Because of the intensive aeration usually associated with MBRs, and then need for anoxic and/or anaerobic conditions to achieve BNR, the two have typically not been utilized within the same reactor systems (Kimura et al., 2007). However, BNR has successfully been achieved using MBRs using various reactor configurations. Optimization of the two processes was the subject of a study that used a modified DEPHANOX system (Bortone et al., 1999 as referenced in Patel et al., 2005) achieving 77.5% TN removal and 96.3% P removal (Patel et al., 2005). Another such study utilized simultaneous nitrification/denitrification in a single reactor tank by inserting baffles into
a typical MBR and changing how the influent was fed (Kimura et al., 2007). This study removed TP and TN at rates of 97% and 77% respectively using a hydraulic retention time (HRT) of 4.7 h (Kimura et al., 2007).

2.4 Biomass Concentrator Reactor

Membrane technology is quickly becoming a highly competitive alternative to conventional systems. As the cost of production and operation become less expensive, this technology will have the potential for an enormous impact on wastewater treatment practices. Testing has been performed on an innovative membrane system with thick walls and larger pore size that allows for solids separation with minimal pressure differential. This biomass concentrator reactor (BCR), developed by EPA-NRMRL and the University of Cincinnati (Patent No. 6821425 issued Nov. 23, 2004), uses thick membranes (~3mm) constructed of packed polyethylene beads with an effective pore size range of 18~28 µm, significantly larger than most membranes used in MBRs (Zhang, 2009). The thickness of the membrane creates solids separation by deep filtration while the larger pore size enables operation without the very large pressure difference between the retentate and permeate that most MBRs require (<2.5cm) (Zhang, 2009). Using a BCR, a pilot scale reactor was tested for MTBE biodegradation at influent concentrations of 5 mg/L, HRT of 4 hours, and flow rate of 2500 L/d with treatment efficiency exceeding 99.9% (Zein, Suidan, & Venosa, 2004). Modifications to the original design have led to a membrane sheet folded around a central collection cylinder which maximizes surface area (Zhang, 2009).
3. Materials and Methods

The objective of this work was to analyze the effectiveness of the BCR in treating municipal waste under conditions of both conventional aerobic treatment as well as multiple zones of aerobic and anoxic treatment for enhanced biological nitrogen removal. This was done by running side by side reactor systems representing the two types of treatment with constant and equivalent flows of synthetic wastewater. Influent and effluent concentrations of various key constituents were measured to evaluate and compare performance of the systems.

3.1 Synthetic Wastewater

Synthetic wastewater composed of various substrates and nutrients (Table 3.1) was pumped at constant flow rate into each reactor. The solution was designed to represent a medium strength wastewater with approximately 200 mg/L COD and 40 mg/L TKN. Concentrated mixtures of organic constituents, nutrients, and buffer were prepared and pumped individually into each reactor along with deionized tap water to reach the desired flow rate of 71.3 L/day. Flow rates were monitored daily by observing the loss of concentrated solution in each reservoir.
Table 3-1. Detached synthetic wastewater composition at BCRs influent after dilution.

<table>
<thead>
<tr>
<th>Component</th>
<th>Final Concentration, mg/L</th>
<th>Component</th>
<th>Final Concentration, mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrates and macronutrients</td>
<td></td>
<td>Micronutrients</td>
<td></td>
</tr>
<tr>
<td>Casein</td>
<td>47.0</td>
<td>Cupric sulfate</td>
<td>0.09</td>
</tr>
<tr>
<td>Tryptone</td>
<td>47.0</td>
<td>Sodium molybdate</td>
<td>0.15</td>
</tr>
<tr>
<td>Starch</td>
<td>84.4</td>
<td>Manganese sulfate</td>
<td>0.13</td>
</tr>
<tr>
<td>Sodium acetate</td>
<td>31.9</td>
<td>Zinc chloride</td>
<td>0.23</td>
</tr>
<tr>
<td>Glycerol</td>
<td>12.0</td>
<td>Iron chloride</td>
<td>0.42</td>
</tr>
<tr>
<td>Caproic acid</td>
<td>11.6</td>
<td>Cobalt chloride</td>
<td>0.42</td>
</tr>
<tr>
<td>Ammonium sulfate</td>
<td>116.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium sulfate</td>
<td>69.6</td>
<td>Buffer</td>
<td></td>
</tr>
<tr>
<td>Calcium chloride</td>
<td>22.5</td>
<td>Sodium carbonate</td>
<td>248.6</td>
</tr>
<tr>
<td>Potassium phosphate</td>
<td>27.6</td>
<td>Sodium Sulfite</td>
<td>162</td>
</tr>
</tbody>
</table>

3.2 Reactors

Two reactors were needed to carry out this research. One is a hybrid reactor (reactor 1) with 2 separate zones (aerobic and anoxic) in order to accomplish nitrogen removal. The other is conventional MBR (reactor 2). Both reactors are composed of a plexiglass cylinder just larger than the membrane modules that sits inside them. Aeration ports are located at in the middle of both reactors 1 & 2 around the bottom of the
membrane module, and at the bottom of reactor 2. This way, the air released can scour the surface of the membrane and simultaneously mix the contents. Feed solutions (organic feed, nutrients, and buffer) are introduced into the reactor from ports located in the bottom half of the reactors. Retentate containing biomass remains around the membrane module while permeate is collected from the bottom of the membranes and discharged through ports located in the effluent column. The aerated and non aerated portions of reactor 1 are separated by a thin plastic funnel with a 3” opening in the middle. This allows for the flow of mixed liquor while inhibiting mixing across zones. A pump with connections to opposite ends of the anoxic zone of reactor 1 is utilized to achieve mixing in this zone. Both reactors are also fitted with pumps designed to take mixed liquor from the bottom of the reactor and return it to the top. In reactor 1, this allows for nitrate from the aerobic zone to be transferred to the anoxic zone for denitrification. In reactor 2, the purpose of this recycle is only to return any biomass that may settle below the air diffusers to the reactor. The volumes of the aerobic and anoxic zones in reactor 1 are 12.5 L and 15L respectively while the volume of reactor 2 is 28.1 L. The membrane module has a surface area of 0.6 m$^2$ (6.4 ft$^2$) and effective volume of 1.9 L. See Figure 4-1 on page 12 for a schematic drawing of the reactor systems.

3.3 Testing and Measurements

Both reactors were sampled on a twice a week basis to monitor SS (suspended solids) concentration, COD (chemical oxygen demand) removal, and nitrogen removal. A
complete list of the tests that were used, the associated method, and the instrument are shown in table 3-3.

**Table 3-2.** Testing and measurement schedule with associated methods and instruments.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Frequency</th>
<th>Method</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rates</td>
<td>Daily</td>
<td>Daily record keeping of reservoir levels</td>
<td>NA</td>
</tr>
<tr>
<td>pH</td>
<td>Daily</td>
<td>pH meter</td>
<td>Oakton WD-35801-00 pH Electrode</td>
</tr>
<tr>
<td>TSS/VSS</td>
<td>Twice Weekly</td>
<td>Standard method 2540D/2540E</td>
<td>Ohaus AP250D Scale</td>
</tr>
<tr>
<td>COD</td>
<td>Twice Weekly</td>
<td>HACH Spectrophotometer Method #8000</td>
<td>HACH DR/2000 Spectrophotometer</td>
</tr>
<tr>
<td>Ammonia</td>
<td>Twice Weekly</td>
<td>Ammonia meter</td>
<td>Orion 9512HPBNWP Ammonia Electrode</td>
</tr>
<tr>
<td>Nitrate</td>
<td>Twice Weekly</td>
<td>Ion Chromatographic Method</td>
<td>Dionex LC20 Ion Exchange Chromatograph</td>
</tr>
<tr>
<td>TKN</td>
<td>Twice Weekly</td>
<td>HACH Spectrophotometer Method #8075</td>
<td>HACH Digesdahl Digestion Apparatus 23130-20 &amp; HACH DR/2000 Spectrophotometer</td>
</tr>
</tbody>
</table>
4.0 Research Plan

The reactors were assembled in accordance with the description and schematic found in Figure 4-1 and Table 4-1 shows operational parameters. Biomass from the local wastewater treatment plant was used to seed the reactors initially. Synthetic wastewater was then provided on a continual basis until the experiment was complete. Temperature was maintained at 20±3ºC and dissolved oxygen (DO) was kept at >6 mg/L and <0.1 mg/L in aerobic and anoxic sections respectively. Initially, no sludge was wasted while the biomass acclimated to the reactors. During this time, monitoring of the reactors was performed using the method in section 3.3 of this document. After sufficient time for acclimation had been given, sludge was wasted by removing a specified volume of mixed liquor from the reactors. Adjustments to air flow, mixing frequencies, or recycle ratio were made as deemed necessary.

The experiment was performed over the course of 350 days for start up and two runs representing different sludge ages (6d & 15d). This was controlled by wasting 1/6th of the volume of each reactor for 6d sludge age, and 1/15th of the volume of each reactor for 15d sludge age. Data collection continued throughout the entire process, both leading up to steady state, as well as during steady state. Daily cleaning of the membranes was done by using a pump that will recycle mixed liquor at a high enough rate to spray clean the membranes in the parts of the membranes not exposed to the turbulence from air flow.
Figure 4-1. Schematic of the reactor setup

Table 4-1. Operational Conditions

<table>
<thead>
<tr>
<th></th>
<th>Reactors 1 &amp; 2</th>
<th>Start Up</th>
<th>Run 1</th>
<th>Run 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>0 - 85</td>
<td>86 - 177</td>
<td>178 - 350</td>
<td></td>
</tr>
<tr>
<td>HRT (hrs)</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>SRT (day)</td>
<td>6</td>
<td>6</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Recycle Ratio</td>
<td>2 - 3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
5.0 Results

5.1 Total and Volatile Suspended Solids TSS/VSS

TSS and VSS concentrations were measured on a twice a week basis during the duration of the experiment. This measurement was taken separately for both sections of reactor 1 as there were often times a significant difference between the two sections. Figure 5-1 shows the TSS concentration in both reactors as well as each section of reactor 1 while figure 5-2 shows the total solids mass in each reactor calculated from the concentration measurement. Despite fluctuations in concentrations week to week, gravity separation of biomass was achieved by the BCR module. Effluent quality remained very clean with tests showing concentration of solids below 1 mg/L in both reactors.
Figure 5-1. Total suspended solids concentrations for both reactors

![Graph showing TSS concentrations for different reactors and runs.]

- Aerobic, Reactor 1
- Anoxic, Reactor 1
- Reactor 2

Run 1 (SRT 6d)  Run 2 (SRT 15 d)
As can be seen from the figures above, reactor startup time allowed the reactors to reach steady state prior to run 1. Since this was not the case for run 2, extra time was needed for the run in order to observe enough data after the reactors reached steady state.
5.2 COD Removal

COD removal was successful in both reactors at both sludge ages. Figures 5-3 shows the influent and effluent COD concentrations. The spike in effluent COD concentration in reactor 2 during the 6 day sludge age was due to a membrane fouling problem that led to the loss of biomass through an overflow line. From these data, removal rates were calculated to be 95% and 97% for reactor 1 for the 6 day and 15 day sludge ages respectively, and 93% for reactor 2 for both sludge age conditions.

Figure 5-3. COD influent and effluent concentrations for both reactors
By comparing the COD consumed to the VSS produced, an observed yield can be calculated and compared between reactors. Figure 5-4 shows the cumulative COD consumed plotted against the cumulative VSS produced for both reactors and both sludge age conditions.

**Figure 5-4.** VSS produced vs COD removed for both reactors and both condition

5.3 Nitrogen Removal

Several forms of nitrogen were measured to represent the various pathways of nitrogen through the treatment systems. The nitrogen in the influent can be measured as TKN since negligible amounts of nitrate and nitrite are present. The nitrogen then either is wasted with sludge daily, released in the effluent as nitrate, nitrite, and TKN, or released to the atmosphere via biological nitrification and denitrification processes. TKN influent and effluent are shown in figure 5-4, ammonia effluent concentrations are shown in figure 5-5, and nitrate and nitrite effluent concentrations are shown in figure 5-6.
Figure 5-5. TKN influent and effluent concentrations for both reactors

![Graph showing TKN concentrations for Reactor 1, Reactor 2, and Influent over time for Run 1 (SRT 6d) and Run 2 (SRT 15d).]
Figure 5-6. Effluent concentrations for both reactors

- Reactor 1
- Reactor 2

Run 1 (SRT 6d)  Run 2 (SRT 15 d)
Nitrogen removal was calculated using the equation below.

\[
\%N_{\text{Removal}} = \left[ 1 - \left( \frac{TKN_{\text{inf}} - NH_3_{\text{eff}} - NO_3_{\text{eff}} - NO_2_{\text{eff}}}{TKN_{\text{inf}}} \right) \right] \times 100\%
\]

TKN in the mixed liquor was measured five times throughout the experiment yielding average TKN/TSS of 11% ± 1%. By multiplying this value by the TSS wasted per day and dividing by the flow rate, the concentration of nitrogen wasted can be determined. The mass balance is then completed by subtracting the concentration of nitrogen from both the effluent and waste from the influent concentration. The resulting value represents the concentration removed through biological denitrification and
subsequent diffusion to the atmosphere. Table 5-1 shows the percent nitrogen calculated for the various pathways for all conditions.

**Table 5-1:** Percent of total nitrogen distribution through various pathways

<table>
<thead>
<tr>
<th>Sludge age</th>
<th>Reactor #1</th>
<th>Reactor #2</th>
<th>Reactor #1</th>
<th>Reactor #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 day</td>
<td>21.0%</td>
<td>20.0%</td>
<td>59.0%</td>
<td>47.0%</td>
</tr>
<tr>
<td></td>
<td>20.0%</td>
<td>22.0%</td>
<td>31.0%</td>
<td>23.0%</td>
</tr>
<tr>
<td>15 day</td>
<td>25.0%</td>
<td>20.0%</td>
<td>55.0%</td>
<td>23.0%</td>
</tr>
<tr>
<td></td>
<td>20.0%</td>
<td>20.0%</td>
<td>20.0%</td>
<td>20.0%</td>
</tr>
</tbody>
</table>

**6.0 Conclusion**

Two things can be concluded from the experimental results. The first, is that the separation process can be achieved using the force of gravity only, with a minimal difference in head between the permeate and the retentate sides of the membrane, and while maintaining low turbidity effluent. The second is that the BCR has the capability to remove COD and nitrogen from synthetic municipal wastewater to the quality of other MBR systems being researched. Table 6-1 shows the BCR experimental results next to some MBR systems. Because the BCR operates with much smaller head differential than traditional MBRs the potential exists to treat wastewater with the same quality and ease of operation that MBRs provide, without the typical downside of high energy requirements.

**Table 6-1.** Experimental results compared to other MBR systems

<table>
<thead>
<tr>
<th></th>
<th>HRT (hrs)</th>
<th>SRT (days)</th>
<th>COD removal (%)</th>
<th>TN removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor 1</td>
<td>9</td>
<td>6</td>
<td>95</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>6</td>
<td>97</td>
<td>75</td>
</tr>
<tr>
<td>Reactor 2</td>
<td>9</td>
<td>6</td>
<td>93</td>
<td>53</td>
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<tr>
<td></td>
<td>15</td>
<td>6</td>
<td>93</td>
<td>43</td>
</tr>
<tr>
<td>Patel et al.</td>
<td>12</td>
<td>20</td>
<td>99</td>
<td>77</td>
</tr>
<tr>
<td>Kimura et al.</td>
<td>4.7</td>
<td>29</td>
<td>85</td>
<td>77</td>
</tr>
</tbody>
</table>
7.0 References


