COMPARISON OF BIOFILM MEDIA IN RECIPROCATING BIOFILTERS
TREATING DAIRY FLUSHWATER

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Master of Science in Civil and Environmental Engineering

by
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ABSTRACT

Comparison of Biofilm Media in Reciprocating Biofilters Treating Dairy Flushwater

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Reciprocating biofilters known as ReCip is a viable technology to manage nutrients, mainly nitrogen, problems at livestock operations such as swine farms and dairies. Past studies have demonstrated that ReCip is more adept at total nitrogen (TN) removal than traditional subsurface flow wetland systems. The traditional substrate used to attach biomass was rock aggregate; this media may be hard to obtain for some agricultural projects, so alternate substrates are tested and compared with the rock aggregate. The purpose of the study was twofold: first, different biofilm media were tested and compared in terms of treatment performance and, second, the long-term performance of a ReCip in continuous operation for 3 years was characterized.

Four, 2.67 square meter ReCip systems with different treatment media – rock aggregate, recycled concrete aggregate (RCA), vertical-flow plastic media, and walnut shells – were operated at a 2-day THRT over the course of a 16 week study. The TN removal efficiencies for rock aggregate, RCA, plastic media, and walnut shell media were 43%, 53%, 25%, and 69% respectively. Surface based mass TN removal rates for the same media were 103, 128, 172, and 276 kg/ha-d respectively.

A 134.2 square meter ReCip with rock aggregate media was running concurrently with the smaller ReCip systems. This ReCip was constructed and operated since January 2010. TN removal efficiency and mass removal rate were 44% and 105 kg/ha-day. These values were close to results from the smaller rock media system.

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CHAPTER 1

Introduction

1.1 ReCip Technology

Reciprocating biofilters known as ReCip® systems use fill and drain sequences between two basins filled with treatment substrate to achieve greater aerobic and anaerobic treatment than conventional subsurface flow (SSF) wetland systems. A head-to-head comparison between gravity flow (conventional wetland) and reciprocating wetland systems concluded that reciprocating systems were more efficient at ammonia, BOD, and TSS removal (Leonard et al., 2000). The ReCip (United States Patent 5,863,433, Behrends 1999) developed by the Tennessee Valley Authority (TVA) uses a cyclic pattern of fill, rest, and drain conditions in a SSF wetland (or fixed film biofilter) to provide the aerobic and anoxic environments needed to improve nitrogen removal: an aerobic environment for oxidation of ammonia to nitrate (nitrification); and an anoxic environment to reduce the nitrate to nitrogen gas (denitrification). The additional benefit to performing nitrification and denitrification in the same system is influent BOD is used as the carbon source as an electron acceptor in the reduction of nitrate. ReCip systems are proven to be effective in treating a variety of wastewater.

1.2 Previous Studies

ReCip systems are proven to effectively treat agricultural wastewater at pilot and commercial scale. The commercial scale demonstration systems Stirling Farms, located near Aliceville AL and Corbett Farm #2 in Duplin County, NC both treated swine units. The pilot scale ReCip at California State Polytechnic University San Luis Obispo, CA

(Cal Poly) was the first ReCip to treat dairy wastewater. It is dairies that are unable to balance their nutrient supply that will need treatment technologies (Henneman 2011). The following summary of projects focuses on the nitrogen removal of those systems.

1.2.1 Stirling Farms near Aliceville, Alabama (Behrends 2002)

The commercial sized demonstration system used two ReCip units (four basins in total) in series to treat swine wastewater from an anaerobic lagoon. The total system size was .32 ha and each basin was filled with 1.5 m of rock aggregate media. The system was operated with 12 reciprocation cycles per day and underwent two yearlong studies with parameter and results listed in **Table 1**.

Table 1. Percent removal and removal rates for ReCip at Stirling Farms. Year I represents testing period from February 2001 through January 2002. Year II represents testing period from February 2002 through October 2002. Negative removal rates mean generation during treatment

	Flow (m ³ /d)	HRT (days)	% Removal			Removal Rates (kg/ha-day)			
			CBOD ₅	NH ₄ -N	TKN	CBOD ₅	NH ₄ -N	TKN	NO ₃ -N
Year I	107	9	79	84	84	127	93	125	-42
Year II	208	4.5	77	91	82	217	198	214	-52

1.2.2 Corbett Farm #2 in Duplin County, North Carolina (Rice 2004)

The commercial scale ReCip test system treating swine wastewater with a solids separator for pretreatment had total system size of .131 ha. The system was operated from December 2002 through January 2004 with 10 reciprocation cycles per day at an HRT of 6 days, based on the total capacity of both wetland cells. That equates to a 3-day HRT when HRT is calculated from capacity of the wetted volume (only one cell). Loading rate was 75.7 m³/d (20,000 gpd). The system achieved 87.5% total nitrogen removal with a removal rate of 219 kg/ha/d of total nitrogen.

1.2.3 Cal Poly ReCip System, California

Cal Poly has currently operated a 0.01342 ha sized pilot-scale ReCip systems treating dairy wastewater from an anaerobic lagoon. This system was construed in 2009 and several projects have been run to analyze its treatment performance. The most recent study conducted on the Cal Poly ReCip was a hydraulic loading study (**Table 2**).

Table 2. Removal efficiencies and rates for hydraulic loading study at Cal Poly ReCip (Starnes 2011). Testing period was from January 1, 2011 through August 31, 2011. HRT for each period are in parenthesis

Time Period and Hydraulic Loading	Location	CBOD5 (mg/L)	TAN-N (mg/L)	TKN-N (mg/L)
1 January - 3 May 8.7 m ³ /day (4.4 d)	% Removal	68	90	70
	Loading (kg/ha-day)	544	120	169
	Removal (kg/ha-day)	371	107	119
4 May - 24 May 10.9 m ³ /day (3.5 d)	% Removal	55	89	70
	Removal (kg/ha-day)	190	157	181
25 May - 8 July 13.1 m ³ /day (2.9 d)	% Removal	58	88	69
	Loading (kg/ha-day)	397	207	282
	Removal (kg/ha-day)	229	182	194
9 July - 28 July 15.2 m ³ /day (2.5 d)	% Removal	51	82	64
	Removal (kg/ha-day)	156	137	164
29 July - 31 August 17.4 m ³ /day (2.2)	% Removal	54	88	66
	Loading (kg/ha-day)	316	214	328
	Removal (kg/ha-day)	169	188	217

Differences in influent water quality, pretreatment method, systems configuration, and data reported make direct comparisons between systems, and different tests on the

same system, difficult when trying to find optimal operational parameters. Influent constituent concentrations directly affect organic loading on the systems and is a parameter that cannot be controlled at commercial and pilot scale.

1.2.4 Media Study

Rock aggregate substrates such as limestone cobble and gravel are traditionally used in ReCip and SSF wetland system (Behrends 2009). There could be systems built where access to rock aggregate is costly and difficult to obtain, thus the need to explore alternate substrate options. Previously a laboratory batch loaded study was conducted to test different substrate configurations (Behrends 2009). Substrates tested included empty lagoon, plastic bioballs, and a combination of bioballs and chipped fiber mats. The results from that study the chipped mats had the best removal efficiency and a higher water volume treated, so more mass of ammonia was removed. The plastic bioballs did not perform well against the rock media and geo-textile mats. The problem with running batch studies is that there is no addition of BOD to achieve denitrification, so TN removal cannot be determined.

1.3 Present Work

Two main studies were conducted during the thesis research: first, different biofilm media were tested and compared in terms of treatment performance and, second, the long-term performance of a ReCip in continuous operation for 3 years was characterized. All five pilot systems were operated with the same hydraulic residence time, based on liquid volume in the pores. Thus, the flow rate through the units with more porous media was greater than that received by the lower porosity units.

Four smaller pilot-scale systems were constructed at the Cal Poly dairy to run a side-by-side comparison of treatment media. Substrates chosen for this study were ones that would be available for use at a California dairy. Recycled concrete aggregate has similar to the rock aggregate. Vertical-flow plastic media is commercially available from different vendors and is used primarily in trickling filter systems. Walnut shells were chosen because it is an agricultural waste product in California that has potential to be reused to treat wastewater. There are no previous systems that use walnut shells as a substrate for biological nitrogen removal. Walnut shells are sometimes used as an alternative adsorbent. A smaller rock ReCip system was established for two purposes: to compare the different substrates to traditional media, and to compare the treatment between different sized systems with the same substrate configuration to validate scalability of the results. The current ReCip system was run in conjunction with the smaller ReCip systems. All systems will be analyzed for water quality, and sludge accumulation to compare the merits and problems of each substrate.

CHAPTER 2

Methods and Materials

2.1 Site Description

Cal Poly operates a flush dairy that consists of a milking parlor, free-stall barns, and 2 storage lagoons; only one lagoon is in use at a time. Over the course of this study the barns contained 350 to 400 animal units of dairy cows; an animal unit is defined as one adult cow, and young cows are counted as half of an adult cow. The barns were flushed two times per day and the water passes through settlers and a screen before entering the storage lagoon. Water from the lagoon was used from the barn flushes. It is estimated that 20,000 gallons and 5,000 gallons of fresh water are flushed from the milking parlor and hospital barn daily. From August 3rd, 2012 to the end of the experiment Cal Poly Farm Operations flushed the barns with fresh water which increased the estimated fresh water flow into the lagoon to 90,000 gallons per day.

2.2 System Specifications and Operational Parameters

A total of 5 pilot scale ReCip systems, running in parallel configuration as shown in **Figure 2**, used the storage lagoon water as influent to be treated. A head tank, continuously replenished with lagoon water was installed to limit the number of pipes and hoses that crossed the access road between the lagoon and the ReCip systems. Influent wastewater was pumped from the head tank to each system. As shown in **Figure 1**, there is a larger system and four smaller systems. All of the ReCips are operated on two-hour over and back pump cycles, repeated twelve times a day except for the plastic media which required one-hour cycles to keep the media wet.

Figure 1. (Right) Flow schematic for the ReCip Systems.

Figure 2. (Left) Photograph of the ReCip systems located at the Cal Poly Dairy. Wastewater is pumped from the lagoon to the head tank, and then disrupted to the systems. Schematic is not to scale.

The hydraulic loading rates of each system were programmed to apply a two-day theoretical hydraulic retention time (THRT) based on clean-bed water volumes of a full tank. These water volumes are determined from tank size and porosity of the media as shown in **Table 3**. The other option in operating the systems would be to apply the same hydraulic (and organic) load to each system. Retention time was favored over loading rate as the determining factor for wastewater application since changes in HRT have shown to affect removal rates. Using HRT as a basis to set flows give advantages to systems with greater water volumes, but increased water volumes are desirable since it can decrease system size.

A two-day THRT was to slightly increase the hydraulic loading from the 2.2 day THRT as per Starnes (2011). The THRT to obtain maximum nitrogen removal has yet to be found. Different organic loading rates from study to study make it difficult to compare the effect of retention time and treatment.

Table 3. Tank characteristics to determine wastewater flows needed to maintain 2 day THRT in each system

System	Empty Tank Volume (m ³)	Porosity	Clean Bed Void Volume (m ³)	THRT (d)	Flow Rate (m ³ /d)
Rock Media (Large ReCip)	74.21	0.49	36.36	2	18.18
Rock Media (Small ReCip)	1.14	0.43	0.49	2	0.246
Recycled Concrete Aggregate	1.14	0.43	0.49	2	0.246
Vertical-flow Plastic Media	1.14	0.97	1.10	2	0.561
Walnut Shell Media	1.14	0.71	0.81	2	0.405

Flow rate measurements were taken twice a week, on Saturdays, and on Tuesdays to ensure that pumps provide the correct amounts of wastewater to maintain a two-day THRT.

2.2.1 Large ReCip System

A concrete two-basin ReCip system has been operated at Cal Poly since October 2009. Each basin dimensions were 11.0 m x 6.1 m x 4.3 m (36 ft x 20 ft x 4.3 ft) with a sump with an area of .83 m². The top media surface area is 134.2m². Along the bottom of each basin were five rows of plastic chambers (BioDiffuserTM Model 1400BD); these chambers were 0.36m (14 in) tall with a bottom width of 0.71m (28 in) and a top width of .41m (16in). The bio diffusers are designed for leach field drainage, in the ReCip system they act as chambers that accumulate sludge; each chamber is connected to a port that should allow for sludge removal in the future. Three 10 cm diameter standpipes were placed in each chamber to measure sludge accumulation across the ReCip basins.

The basins were filled with three layers of rock aggregate: 30 cm of greywacke cobblestone (15-25 cm diameter) on the bottom; the middle was 23 cm of crushed granite rock (5-10 cm diameter); the top layer was 64 cm of smaller crushed granite rock (2-4 cm diameter). Clean bed porosity of the top layer was calculated to be 0.40, while the

porosity of the system was calculated to be 0.49 (Starnes 2011). The influent basin water level was controlled by a weir located by the sumps; the water level in the effluent tank was controlled by a weir as shown in **Figure 2**. The system received 18.18 m^3 (4800 gallons) daily. Wastewater was pulsed into the system once each cycle when the influent tank was drained down.

Due to sludge accumulation in the system, the water elevations and pump times differed from the studies by Kane (2010), Henneman (2011), and Starnes (2011). The water elevations cycled between 110 cm and 30.5 cm (43.3 in and 12 in) during filled and drained sequences. Pumping sequences were set to 22 minutes each; rest periods increased to 48 minutes. The sump pumps were fitted with float valves to prevent from running dry.

2.2.2 Small ReCip Systems

Each of the smaller ReCip systems were filled with different treatment media and constructed from two tote tanks (Schutz MX 1250) each. The dimensions of each tote tank were 1.17 m x 0.94 m x 1.14 m (46 in x 37 in x 45 in). Treatment media used included rock aggregate, recycled concrete aggregate (RCA), vertical-flow plastic media (Brentwood Industries AccuPac VF-3800), and walnut shells show in **Figure 3**.

Figure 3. Photographs of small ReCip systems: Rock Aggregate (Top Left); Recycled Concrete Aggregate (Top Right); Vertical-flow Plastic Media (Bottom Left); Walnut Shells (Bottom Right)

All systems except the plastic media have sludge chambers using a smaller chamber (Advanced Drainage System Inc. ARC™ 18) with dimensions 30.5 cm in height, 15 cm in top width, and 40 cm in base width; there was one chamber per tank. The rock, RCA, and walnut system also had a 30.5 cm greywacke cobblestone layer on the bottom surrounding the chamber. The layers in the rock system was set to mimic the larger system with middle and top layers of crushed granite rock with the same thickness as the large system. The RCA (1-2 cm diameter) and walnut shell (1.3-2.6 cm diameter) systems contained 87 cm of media above the cobblestone layer. Each of these systems also had sumps constructed from 15.24 cm (6 in) diameter pipes. These three systems have a top media surface area of 2.14 m².

The vertical-flow plastic media ReCip contains no cobblestone layer, plastic chamber, or sumps made from pipes. The plastic media was supported on four concrete blocks with dimensions 39.4 cm x 19 cm x 19 cm (15.5 in x 7.5 in x 7.5 in). A 25.4 cm x

30.5 cm (10 in x 12 in) section cut into the plastic media in each tank created room for sumps. The plastic media cross sectional area was 1.03 m x 0.91 m (40.5 in x 36 in) and left some open space along the edges of the tank. The media top surface area is 1.72 m² for the system.

All systems were operated at the same water elevations and THRT as the large system. The sumps in the small ReCip systems did not have enough space for float switches; each sump pump was checked and set every Saturday so the drained tank water level of was 30.5 cm in each tank. The ReCip times were different for each pump, ranging from 20 minutes to 23 minutes. Each of the systems receive waste water as per **Table 3**: the rock and RCA systems receive 0.246 m³/d (65 gpd), the plastic system receives 0.561 m³/d (146 gpd), and the walnut shell system receives 0.405 m³/d (107 gpd).

2.2.2.1 Start-up period

The small systems were started up during a six week period starting June 2, 2012. During the first week the systems were filled with one quarter wastewater and three quarters tap water. During the second week the systems were filled with half wastewater and half tap water. From the third week the systems started to receive continuous flows. The starting wastewater flow was at a quarter of experimental loading; the flow rate was increased so that each subsequent week the systems would receive an additional quarter of experimental loading until they were operating at full flow. The systems were run at full flow for a week before the first official sample was taken.

2.3 Water Quality Analysis

Water quality samples were taken and analyzed weekly from July 20, 2012 to November 2, 2012. Effluent sample from each system and an influent sample were collected in a 1L bottles around 8:30 in the morning on Fridays. Water temperatures were taken immediately after filling the sample bottles. These samples were analyzed the day of collection with the following methods listed in **Table 4** except for Total Kjeldahl Nitrogen, which was analyzed a week later from preserved samples.

Table 4. Summary of water quality analysis used text in parentheses indicate method from Standard Methods (2005)

Parameter	Method
Total & volatile suspend solids	Fisherbrand Glass Fiber G4 Filters (Methods 2540-B, 2540-D, 2540-E)
Carbonaceous oxygen demand	5-day, 20°C (Method 5210-B)
Total Kjeldahl N (TKN)	Macro-Kjeldahl Method (Method 4500-N _{org} -B)
Total ammonia N (TAN)	Orion 9512 Ammonia Selective Electrode (Method 4500-NH ₃ -D)
Nitrate as N	Orion 9700 Nitrate selective probe (Method 4500-NO ₃ ⁻ D)
Nitrite as N	Colorimetric method (4500-NO ₂ ⁻ B)
Alkalinity as CaCO ₃	Acid Titration (Method 2330-B)

2.3.1 Nitrification and Denitrification Rates

To compare the effectiveness of biological nitrogen removal between the systems it is effective to compare rates of nitrification and denitrification. Crites et al. (2010) use a first order model in their design for subsurface wetland nitrification and denitrification (Equation 1). This model used empirically calculated reactions rates to solve for effluent concentrations. The ReCip is a well-mixed system, but has a complex hydrologic regime

that does not fit a continuous stir tank reactor (CSTR) model (See appendix). A plug-flow reactor first order model was used to determine reactions rates from known influent and effluent concentrations for the basis of comparison of treatment between each other:

$$C_e/C_o = \exp (-K_t t) \quad (1)$$

To calculate nitrification rates (K_t), C_o was the influent TAN concentration, C_e was the effluent TAN concentration, and t was the THRT in days. Calculations for denitrification rates are similar except C_o was the nitrate concentration of the influent plus TAN oxidized during nitrification, C_e was the effluent nitrate concentration. Air quality studies on the ReCip at Cal Poly demonstrated that there is minimal amounts of NH_3 volatilization, thus it is assumed that all TAN was oxidized to nitrate (Henneman, 2011). Previous studies have also demonstrated that change in climate at the project site had minimal impact on removal rates, so a temperature correction to solve for K is not used.

2.4 Sludge Analysis

To determine accumulated sludge in the plastic chambers, the depth of the sludge was measured and multiplied by the area it covers. A 1 cm diameter polyvinyl tube attached to a graduated PVC pipe calibrated in 1 cm increments and connected to a peristaltic pump. The tube attached to the pipe was slowly lowered into the standpipes connected to the chambers of a filled ReCip basin. The height to the sludge from the top of the standpipe was recorded when sludge was observed in the tubing. This height was subtracted from the height of the standpipe to find the depth of the sludge. The sludge depth in the basin for the large ReCip was determined from the average of the sludge depth in the 15 standpipes. The small ReCip systems contained one standpipe per tank; sludge depth was measure using the same procedure.

The ReCip systems seemed to experience clogging of the media during the course of the project. To quantify the clogging, additional porosity test were conducted after the project finished. A flow meter (GPI TM 050 Water Meter) was used to measure the total flow pumped into or out of a tank. The change in height of the water was measured with a measuring tape. A change in height equated to a tank volume; the measured amount of water pumped divided by the tank volume resulted in a porosity measurement. The change in porosity equals the sludge accumulation in the media.

Sludge samples were collected to find solids, carbon, and nitrogen content. A sludge sample was grabbed from the sludge chamber by lowering the sludge measuring pipe to the bottom the tank and slowly drawing the apparatus through the sludge layer to obtain a representative sample. Sludge sample from the pore spaces in the media were scraped off of media about 0.4m from the surface. Samples were taken to measure total and volatile solids as well as carbon and nitrogen content using the Dumas Combustion Method (Vario MAX CNS Elemental Analyzer, Elementar Americas Inc.) Total nitrogen in the sludge was calculated by multiplying solids content by the mass percentage of nitrogen and total volume of sludge (**Equation 2**).

$$\text{Total Nitrogen in Sludge} = \text{TS} \times \%N \times V_s \quad (2)$$

Where:

TS	=	Total Solids (mg/L)
%N	=	Mass percentage of nitrogen in solids
Vs	=	Volume of sludge in both basins

2.5 Mass of Total Nitrogen Removed

The mass removal of nitrogen was calculated using water quality, flow, and sludge accumulation data. Input of nitrogen mass to the systems was the sum of nitrate, nitrite, ammonia, and organic nitrogen (i.e., TKN-TAN) concentrations multiplied by the

influent flow. Output nitrogen mass was the sum of those same constituents multiplied by influent flow and also included total nitrogen of accumulated sludge. By excluding sludge nitrogen from the nitrogen-removed mass, biological nitrogen removal could be analyzed separately from physical nitrogen removal via accumulation of sludge nitrogen. In addition, the sludge and its nitrogen would have to be removed from the ReCip systems in the future.

The sludge nitrogen accumulation rate in the small ReCip systems was calculated using sludge volumes measured in December 2012 and April 2013. With the initial accumulation of zero, the accumulation rate was interpolated between the three dates. Sludge composition of the small ReCip systems was measured in April 2013, and the average nitrogen fraction of the sludge on that date was assumed to be constant.

A true mass balance could not be performed because no air emissions measurements taken during the present study. However, air emissions have been minimal in a past studies: volatilization of ammonia was 0.02% N and nitrous oxide emissions were 0.18% N of the nitrogen mass-balance (Henneman, 2011).

2.6 Surface Area Calculation

The method used for finding specific surface areas of the rock aggregates and RCA comes from the determination of filter media surface area (Crittenden 2005). Since the media are not comprised of uniform spheres, the correction factors sphericity (ψ) and shape factor (ξ) are used. The conceptual meaning of sphericity is:

$$\psi = \frac{\text{surface area of equicalent volume sphere}}{\text{actual surface area of particle}} \quad (3)$$

Shape factor is a dimensionless number that gives a magnitude to sphericity with the following relationship:

$$\xi = \frac{6}{\psi} \quad (4)$$

For perfectly spherical particles $\psi = 1$ and $\xi = 6$. The specific surface area (S) for the media using the correction factors:

$$S = \frac{\xi (1-\varepsilon)}{d} \quad (5)$$

The porosity (ε) of the different media has been determined previously to find tank media parameters. The diameter of the particle (d) is the equivalent diameter of a sphere with the same volume. This method required surface area and volume of particles to be determined. Surface area of particles was found by the foil method (Marsh, 1970), and particle volume was found by water displacement.

The specific surface area of the walnut shells was determined by finding the total surface area using the foil method of a known volume of walnut shells. The specific surface area was total surface area divided by volume.

2.7 Reciprocation Energy Intensity

Energy intensity is an important factor in choosing treatment technologies, and the energy intensity of reciprocation as a method of aeration has not been characterized previously. It differs from systems energy requirements because it pertains to energy used in oxygenation of the system and not the energy used pumping of the influent and effluent.

2.7.1 Oxygen Consumption

Oxygen transfer into wastewater during treatment can be estimated by the difference in the influent and effluent of the mass of oxygen-demanding and oxygen-containing substances, minus the oxygen demand of any sludge accumulated over the

period of study. The resulting value is equivalent to an estimated mass of oxygen consumed per day.

The major oxygen-demanding constituents in the present study were captured in the measurement of CBOD and TKN. Removal of TKN is used instead of TAN because some organic nitrogen degrades to ammonia and is nitrified. In nitrification, the stoichiometric relationship between oxygen and nitrogen is 4.56, in terms of mass. Although emissions of oxygen demanding gases (e.g., methane, hydrogen sulfide, ammonia) were not monitored, emissions of these gases have been minimal in past studies (Henemann 2011, Starnes 2011). Five-day CBOD removal must be converted to ultimate CBOD (CBOD_u) removal to correctly represent the oxygen consumed in the ReCips. No specific conversion factors are known for the Cal Poly Dairy wastewater, so the commonly used value for raw domestic wastewater was adopted: $1.6 \times \text{CBOD}_5 = \text{CBOD}_u$.

Similarly, sludge samples were not tested for CBOD, only TS and VS, so a conversion factor was based on the stoichiometric value of 1.42 g cBOD per g C₅H₇O₂N biomass (as represented by VS). Due to the high content of biologically inert VS in the recycled flushwater (as revealed its high COD/BOD ratio) and the partially degraded nature of the sludge, a VS/CBOD_u conversion factor of 0.7 was assumed.

The major redox sensitive oxygen-containing substances were nitrate, nitrite, sulfate, and dissolved oxygen. While the oxidized nitrogen compounds were monitored closely, dissolved oxygen (DO) and sulfate were not monitored, due to an oversight. However, the large ReCip influent has contained <1 mg/LDO and the effluent has averaged 1.4-1.8 mg/L in previous studies (Kane 2010, Henemann 2011). The emissions

of oxidizing gases (e.g., oxygen, nitrogen oxides) were not monitored in this study, but, as with the reducing gases, the emissions of nitrous oxide and nitric oxide were found to be minimal in the previous studies (Kane 2010, Henemann 2011).

The net oxygen consumed in each ReCip system is assumed to be equal to the atmospheric oxygen input. Assuming the above and that all TKN removed was oxidized to nitrate and all CBOD removed was oxidized to CO₂ by aerobic pathways, oxygen consumption can be estimated (**Equation 6**).

$$\text{Oxygen Consumption (g/d)} = 1.6(\Delta M_{\text{CBOD}_5}) + 4.57(\Delta M_{\text{TKN}}) - 1.0(\Delta M_{\text{DO}}) - 0.7(\text{VS}_{\text{sludge}}) - 4.57(\text{VS}_{\text{sludge}})(\text{ON/VS}) \quad (6)$$

Where:

1.6 = CBOD₅ to CBOD_u conversion assumption

4.57 = oxygen consumed in nitrification of ammonia

ΔM_x = mass of substance x removed ($Q_i C_{ix} - Q_o C_{ox}$), g/d

Q_i = inflow, m³/d

Q_o = outflow, assumed to equal inflow, m³/d

C_{is} = inlet concentration of substance x, g/m³

C_{ox} = outlet concentration of substance x, g/m³

VS_{sludge} = volatile solids concentration of sludge accumulated in the system, g/d

ON = organic nitrogen concentration of sludge accumulated in the system, g/d

2.7.2 Energy Usage

The Cal Poly ReCip systems did not have individual power meters, and the energy usage of the pilot scale systems would not be representative of optimized full-scale systems. Instead the pumping energy per volume of water was estimated using the commercial-scale ReCip system at Stirling Farms, AI USA (Behrends, 2003). This system had top surface area of 0.32 ha spanning four ReCip basins; there was two separate ReCip system configured in series. A rock aggregate media with similar heights to the system at Cal Poly was used at Stirling Farms; the system also ran at 12 cycles per

day. The flow rates, HRT, and energy usage for the ReCip at Stirling Farms for year I and year II were 107 and 208 m³/d, 9 and 4.5 days, and 203 and 234 kWh/day respectively. The porosity of the rock gravel media used at Stirling Farms was not given so a porosity of 0.4 was assumed.

The increased energy used between years I and II was mainly due to increased influent and irrigation pumping; reciprocation times and cycles remained constant. Since there were two values for energy and pumping the amount of energy used for reciprocation was estimated by finding the difference in energy and volume pumped; dividing the two values; multiplying the result by one of the flows; and finally subtracting from the total power. The ratio of reciprocation energy per volume pumped was calculated by dividing the energy for reciprocation by the water volume pumped.

CHAPTER 3

Results

The small ReCips had been operated since June 2, 2012 to begin to develop the biofilms, and the large ReCip had operated from January 2010. From July 20, 2012 through November 2, 2012, comprehensive water quality analyses were conducted for all ReCip systems, as reported in this thesis (**Tables 5 and 6**). Because dairy nutrients are regulated in California primarily on a mass basis, the main variable used below in the comparisons of the ReCip systems is mass removal rate, not final concentration or percent removal. ReCip reactors are shallow and require a fair amount of land space, so a mass-removed-per-hectare basis is used to compare ReCip systems within the present project as well as with previous ReCip studies by others.

In this initial study, hydraulic residence time (HRT) was chosen as the control variable instead of loading. The different porosities of each system led to different hydraulic loading rates and organic loading rates. This approach was thought to improve the use of the inherent potential of each medium, helping to guide media selection. For example, an advantage of the plastic medium is its high porosity and potential for a long HRT in a small footprint. If, instead of equal HRTs, equal loadings were used for all media tanks, then the expensive plastic medium would not have been loaded to its full potential. A longer, more complete study than the present one would require testing each medium at several loading rates to determine the influence of loading on removal.

Table 5. Summary of mean non-nitrogen water quality constituents from July 20 through November 2, 2012. Plus/minus values are standard deviations for the weekly samples. The Large systems had large porosity than small Rock system, so it received a slightly large areal mass loading rate.

Location/System		Temperature (°C)	Alkalinity (mg/L) ¹	TSS (mg/L)	cBOD5 (mg/L)	scBOD5 (mg/L)
Influent	Mean	21.2	2086	920	255	54
	+/-	1.80	439	370	75	20
Large ReCip	Mean	22.1	1508	704	155	17
	+/-	3.15	351	226	91	19
Rock Aggregate (Effluent)	% Removal			23%	39%	69%
	Loading (kg/ha-day)			1246	346	73
	Removal (kg/ha-day)			292	136	50
Small ReCip	Mean	18.6	1347	658	155	19
	+/-	1.65	349	181	77.3	23
Rock Aggregate (Effluent)	% Removal			28%	39%	65%
	Loading (kg/ha-day)			1059	293	62
	Removal (kg/ha-day)			302	115	41
Recycled Concrete Aggregate (Effluent)	Mean	19.7	1195	654	151	16
	+/-	2.08	205	268	74	21
Rock Aggregate (Effluent)	% Removal			29%	41%	71%
	Loading (kg/ha-day)			1059	293	62
	Removal (kg/ha-day)			307	120	44
Vertical Flow	Mean	19.7	1562	745	193	20
	+/-	1.57	600	231	82.1	28
Plastic Media (Effluent)	% Removal			19%	25%	64%
	Loading (kg/ha-day)			2999	831	176
	Removal (kg/ha-day)			570	204	112
Walnut Shell Media (Effluent)	Mean	20.2	1365	457	132	11
	+/-	4.68	325	140	80	14
Rock Aggregate (Effluent)	% Removal			50%	48%	80%
	Loading (kg/ha-day)			1742	483	102
	Removal (kg/ha-day)			877	233	82

¹ Alkalinity is reported as mg/L CaCO₃.

Table 6. Summary of mean nitrogen water quality constituents in weekly grab samples from July 20 through November 2, 2012. Plus/minus values are standard deviations for the weekly samples. The Large systems had large porosity than small Rock system, so it received a slightly large areal mass loading rate.

Location/System		TAN (mg/L) as N	NO ₃ ⁻ (mg/L) as N	NO ₂ ⁻ (mg/L) as N	TKN (mg/L) as N ¹	ON (mg/L) as N ²	TN (mg/L) as N ³
Influent	Mean	160.3	6.5	0.1	248	90.1	254
	+/-	40.8	6.1	0.1	61	29.3	578
Large ReCip Rock Aggregate (Effluent)	Mean	37.0	32.3	0.9	110	73.3	144
	+/-	14.8	9.6	0.5	36	26.0	47
	% Removal	77%			56%	19%	43%
	Loading (kg/ha-day)	217	9		336	122	345
	Removal (kg/ha-day)	167	-35		187	23	149
Small ReCip Rock Aggregate (Effluent)	Mean	37.0	70.1	0.7	117	79.1	191
	+/-	20.7	36.1	0.5	52	37.4	84
	% Removal	77%			53%	12%	25%
	Loading (kg/ha-day)	184	8		283	104	293
	Removal (kg/ha-day)	142	-73		150	13	73
Recycled Concrete Aggregate (Effluent)	Mean	15.6	80.5	0.3	89	72.9	174
	+/-	8.0	54.3	0.2	35.4	28.7	88
	% Removal	90%			64%	19%	31%
	Loading (kg/ha-day)	184	8		283	104	293
	Removal (kg/ha-day)	166	-85		182	20	92
Vertical Flow Plastic Media (Effluent)	Mean	89.2	39.4	1.8	177	85.3	218
	+/-	47.7	24.7	1.1	82	36.8	72
	% Removal	44%			29%	5%	14%
	Loading (kg/ha-day)	522	21		794	294	829
	Removal (kg/ha-day)	232	-107		229	15	120
Walnut Shell Media (Effluent)	Mean	14.7	27.1	0.8	72	57.2	101
	+/-	22.9	23.4	0.7	37	22.0	48
	% Removal	91%			71%	37%	60%
	Loading (kg/ha-day)	304	12		467	171	482
	Removal (kg/ha-day)	276	-39		331	62	289

¹The samples for 10/19/2012 were not tested for TKN and were not included in the averaged value.

²Organic Nitrogen was calculated weekly by taking the difference between TKN and TAN.

³Total Nitrogen was calculated weekly by taking the sum of TKN nitrate and nitrite.

Soon after the start of the experiment described herein, beginning August 3, 2012, instead of using recycled lagoon water the dairy operators began to use freshwater to flush the freestalls. As a results, influent pollutant concentrations declined over the course of the experiment (**Figure 4**). This progressive dilution of the influent was a reason for the large standard deviations of the averaged data in the tables below

Figure 4. Influent concentrations of CBOD₅, TAN, and TKN from July 20, 2012 to November 2, 2012. Progressive dilution of the influent is caused from freshwater flushing of dairy barns starting in August 3 represented by the black line.

3.1 Small ReCip Analysis

Biofilm media types were compared in the small ReCip study. In terms of concentration removal (**Tables 5 and 6**), comparison between medium ranks walnut shell first followed by RCA, rocks, and then plastic. In terms of mass removal, walnut shells performed the best, with plastic media second, RCA third and rock media ranking last. Mass removal rates depended on organic loading and concentration removal. The plastic

removed the second most mass per day despite its poor concentration removal at a 2-day HRT due to receiving the highest organic loading out of all the media.

From July 20 to November 2 the averaged total nitrogen data demonstrates poor removal in the rock, RCA, and plastic medium in comparison with the large systems and walnut shell media. The large system and the small rock system had similar concentration removal for aerobic treatment (CBOD₅, TAN, and TKN removal), but the small system higher effluent concentration for anaerobic treatment (nitrate removal) (**Tables 5 and 6**). The RCA system cannot be directly compared to the large system, but also had good TAN removal with poor nitrate removal. The plastic media had lower effluent nitrate concentrations than the rock and RCA, but had the highest TAN effluent concentrations of all systems. These systems required additional start-up time after July 20.

Biological systems often demonstrate a start-up period when removal efficiencies have not reached steady state due to ongoing development of the microbial populations (Rice 2004). The ReCip system at Corbett Farm required 5 months of startup time, partially due to startup in cold winter weather, until data showed steady state had been achieved (Rice 2004). Time series analysis of concentration removal percentages was used to determine when steady state was achieved. Laboratory analysis of biofilm growth in a simulated subsurface wetland (attached growth sequencing batch reactors) concluded that biomass in their systems can take upwards of 100 days to stabilize (Ragusa *et al.*, 2004). Again graphical analysis was used to determine when steady state conditions were achieved.

Steady state conditions were never achieved for the ReCip systems because the influent conditions were constantly changing. A period that best approximated steady

state was determined by graphic analysis of ammonia and nitrate over time (**Figures 5 and 6**). This period of most consistent performance was determined by finding the sample dates where the effluent concentrations leveled off.

The plastic media required additional start-up time because at 12 reciprocation cycles per day, the biofilm dried between reciprocations leading to poor treatment, and this problem went unnoticed initially. During the first week of the experiment (July 20), the reciprocation rate for the plastic media tanks was doubled to 24 cycles per day. With the tanks drained for shorter periods of time, the biofilm remained moist and treatment improved. As a result, a few additional weeks were needed for startup as demonstrated by the leveling off of TAN concentration by August 31 (**Figure 5**).

Figure 5. Influent and effluent TAN concentrations from June 2, 2012 to November 2 2012. All systems except the plastic media exhibit response to response to change in influent concentrations. Plastic media TAN concentrations start leveling off by August 31. The vertical lines represent the dates where changes in loading occurred during the start-up of the systems described in section 2.2.2.1.

Additional start-up time was required for the rock, RCA, and plastic media systems to reach a point where nitrate concentrations leveled off. The plastic media had increased nitrate effluent concentrations from July 20 through August 31 because the system started nitrifying ammonia. Nitrate concentrations leveled off in the rock and RCA systems from July through September. An approximated steady state is reached starting at the September 21 sample date (**Figure 6**). From September 21 through November 2, averaged influent and effluent concentrations, removal efficiencies, and mass loadings and removal rates were calculated and used for further performance comparison between physical substrates.

Figure 6. Influent and effluent nitrate concentrations from July 20, 2012 to November 2 2012. The increase in nitrate concentrations in the plastic media from July 27 to August 31 is the start-up period following the switch to 24 reciprocation cycles per day. The period where data best approximates steady state conditions is from September 21 through November 2, which is the period used for analysis and comparison of the media

3.1.1 Water Quality and Nutrient Removal from September 21 through November 2

The mean values, removal efficiency, and mass loading and removal rates were calculated for the period between September 21 and November 2 (**Table 7**).

Table 7. Treatment performance by the small ReCip systems during September 21 to November 2, 2012. Negative removal of nitrate was caused by nitrification and incomplete denitrification. Plus/minus values are standard deviations for the weekly samples. These averaged values are used in the discussion of nitrogen removal for each media.

Location/System		cBOD5 (mg/L)	TAN (mg/L-N)	NO ₃ ⁻ (mg/L-N)	TKN (mg/L-N)	TN (mg/LN)
Influent	Mean	195	139	11.8	198	210
	+/-	36	35.0	5.9	15.0	13
Large ReCip Rock Aggregate	Mean	83	35.0	28.4	88.8	118
	+/-	24	11.0	3.3	12.9	11
	% Removal	57%	74%		55%	44%
	Loading (kg/ha-day)	264	188	16	268	284
	Removal (kg/ha-day)	152	140	-22	148	124
Small ReCip Rock Aggregate	Mean	98	24.8	39.7	77.8	120
	+/-	17	8.5	9.3	16.5	16.5
	% Removal	50%	81%		61%	43%
	Loading (kg/ha-day)	224	159	14	228	241
	Removal (kg/ha-day)	112	131	-32	138	103
Recycled Concrete Aggregate	Mean	93	10.0	35.8	59.0	98
	+/-	23	5.0	12.0	14.3	22
	% Removal	53%	93%		70%	53%
	Loading (kg/ha-day)	224	159	14	228	241
	Removal (kg/ha-day)	118	148	-28	160	128
Vertical Flow Plastic Media	Mean	128	63.8	32.7	123.7	157
	+/-	24	26.9	17.1	32.1	27
	% Removal	35%	55%		38%	25%
	Loading (kg/ha-day)	636	452	39	646	683
	Removal (kg/ha-day)	220	244	-24	243	172
Walnut Shell	Mean	62	7.1	17.4	44.5	64
	+/-	12	3.9	5.9	7.0	11
	% Removal	68%	94%		78%	69%
	Loading (kg/ha-day)	370	262	22	375	397
	Removal (kg/ha-day)	251	249	-6	291	276

Averaged influent and effluent conditions for the period from September 21 through November 2 differed from the averages from July 20 through November 2. Averaged removal percentages of CBOD₅, TAN, TKN, and TN were higher in the small ReCip systems from September 21 through November 2 than they were from July 20 through November 2. Decreased CBOD₅, TAN, TKN, and TN influent concentrations and steadied effluent concentrations resulted in greater removal percentages. Averaged mass loading and removal rates were generally lower from September 21 through November 2.

3.1.2 Nitrification and Denitrification Rates

Nitrification and denitrification rate constants are another way to express nitrogen removal and compare media effectiveness. For mass transfer into the biofilms, it is ideal to know the concentration near the biofilm, but due to sludge accumulation and the changes in conditions in the tanks over time of the reciprocation cycle this concentration is difficult to measure. A first order plug-flow model takes into account the bulk concentration in the tanks and can be used to compare the nitrification and denitrification between media. Reciprocating between two tanks results in an unusual hydraulic regime because treated wastewater only leaves the system when the effluent tank is filled. As a result, it is difficult to use removal models based on ideal hydraulics to predict removal during various loading rates. As a preliminary effort, the ideal first-order plug-flow model was used. Average nitrification and denitrification rate constants (k) based on effluent concentrations for each medium were calculated (**Table 8**). These rate constants are calculated from influent and effluent nitrogen species concentrations and

THRT. The equations used to determine these rates constants are show in Section 2.5.1 in the Methods chapter.

Table 8. First order steady state plug flow nitrification and denitrification rate constants for ReCip systems at Cal Poly Dairy. Rates determined from data-set from July 20 to November 2. HRT = 2.0 days

	Rock	RCA	Plastic	Walnut shells
Nitrification rate (1/d)	0.88	1.40	0.42	1.55
Denitrificaion rate (1/d)	0.56	0.69	0.43	1.06

The rank in nitrification and denitrification rate constants for the systems is similar to the concentration removal of TAN and TN. The walnut shells had the highest nitrification and denitrification rate constants, but the RCA was similar for nitrification constant only. The difference in nitrification and denitrification rate constants between the rock and RCA is probably due to media size. The RCA granules are smaller than the rock granules and the media has a higher surface area for growth of biofilms (**Table 9**).

3.1.3 Nitrogen Removal Based on Media Surface Area

The mass removal rates can be normalized by the surface area of active medium in each system, thereby allowing a rough comparison of the removal performance of the biofilm on the media surfaces. Of course, this analysis is confounded by sludge accumulation in the media, changing the area available for biofilm growth, but by using removal data from only early in the operation of the system, this sludge effect can be minimized. The nitrogen removed per surface area of media may prove insight to biofilm activity. In this analysis only the original clean-bed media surface area of one tank – the one exposed to the atmosphere at any one moment – for each system is considered; only the surface area that was exposed to both air and wastewater by fill and drain cycles is considered herein. The portion of media that is always submerged is assumed to be less active than the portion exposed to the atmosphere during reciprocation. The surface area

of the tank walls was not considered. To clearly compare treatment performance of media, equal loadings would have to be provided in addition to having no obstruction of the media surfaces by sludge. The specific surface area for the medium and the total active media surface area for one tank of each system were listed along with nitrogen removal (**Table 9**).

Table 9. Media specific surface area, tank exposed media surface area, and TN removal per media surface area for each small ReCip system. The plastic media was loaded at a higher rate than the other media giving it a greater opportunity to removal N mass compared to the other media.

Specific Surface Area of Media (m ² /m ³)			
Rock (2-4 cm)	RCA	Plastic	Walnut Shell
311	544	131	360
Media Surface Area in One Tank Affected by Fill and Drain Cycles (m ²)			
Rock	RCA	Plastic	Walnut
243	516	80	341
TN Removed per Area Media Surface Affected by Fill and Drain Cycles (mg/m ² -d)			
Rock	RCA	Plastic	Walnut
102	57	441	176

According to this parameter, the plastic produces the most active biofilm out of the substrates tested. The vertical-flow plastic media has the lowest specific surface area of all the media analyzed, yet the plastic media system removed the second-greatest mass of nitrogen, no doubt due at least in part to greater removal opportunity from the high loading it received. Vertical-flow plastic media are usually used in flow-through systems such as biotowers, and their high porosity/low specific surface area are what presumably lead to its lower nitrogen removal per tank volume compared to the other media. It does, however, have the advantage of shedding sludge and biofilm through its vertical channels, preventing clogging. For the plastic medium, the nitrogen removal per medium surface area was not confounded by sludge accumulation.

The granules of the RCA medium were smaller in size than the rock medium. The RCA system had more surface area and had better nitrogen removal rates than rock system. However, on a removal per medium surface area, the RCA was the lowest performing medium.

The walnut shells achieved a high value for removal per area of media surface. This factor, combined with its large specific surface area resulted in the highest mass removal rate of the four media (**Table 7**). The sludge accumulation in this substrate was substantial and biofilm performance alone cannot be judged by this experiment

3.1.4. Sludge Accumulation and Analysis

Solids accumulated in the plastic chamber underdrains on the floor of each system and in the pore spaces of the media. In the media beds, solids settled or were filtered from the water and biomass grew and sloughed off the media.

Sludge layer thickness in the chambers of each the small ReCip system was measured in October 2012 and again in December 2012. On both dates no sludge layer could be detected in the chambers of either the influent or effluent tanks for any small Recip systems.

Accumulation in the media bed was monitored via changes in porosity. The porosities of the small ReCip systems were measured in December 2012 and again in April 2013 (**Table 10**). The walnut shells accumulated sludge more rapidly than the other media, and a significant reduction of void-space was observed. One likely explanation is that the walnut shells exhibited a 50% TSS removal over the experimental period, which was much greater than the other media (**Table 5**). The likely cause of the more extensive sludge accumulation in the shells was the high initial porosity of the shells (0.7) and the

interlocking cup-shape of the broken shells. These provided lots of volume for settling and poor migration of the sludge to the floor during ReCip water level changes. The TSS removal percentage for rock and RCA were 28% and 29%, and granules in these media were not shaped to hold sludge as well as the shells. As would be expected for plastic trickling filter media with large vertical channels, no change in porosity in the plastic media was measured through April 2013, and very little sludge was observed in the system. Final HRT in December 2012 estimated from the change in porosity from the original were 2.1, 2.5, and 2.8 days for rock, RCA and walnut shells respectively.

Table 10. Porosity measurements for the small ReCip systems after the experimental period (July 20, 2013 through November 2, 2012). For both 2012 and 2013 values for this table, the change in porosity was calculated between the starting porosity of a clean bed and the measured values (Table 3). A sludge volume was calculated based on the reduction of void-space. *From January 2013 through March 2013 the walnut shell system was operated at twice the influent hydraulic load, which is an experiment not included in this thesis.

Date	System	Influent Tank Porosity	Effluent Tank Porosity	System Average Porosity	Change in Porosity (Compared to Initial Porosity)	Sludge Volume (m ³)
December 2012	Rock	0.45	0.38	0.41	0.02	0.02
	RCA	0.36	0.35	0.35	0.08	0.09
	Walnut Shell	0.54	0.47	0.50	0.21	0.23
April 2013	Rock	0.37	0.37	0.37	0.06	0.07
	RCA	0.36	0.37	0.36	0.07	0.08
	*Walnut Shell	0.43	0.44	0.44	0.27	0.31

Sludge samples from the ReCip systems were analyzed for total and volatile solids content (TS and VS), as well as carbon and nitrogen content (**Table 11**). The sludge trapped in the walnut shell substrate had the lowest ash content at 36%; the walnut shells have a higher sludge deposition rate compared to the rock and RCA, which means that the sludge sampled for the rock and RCA systems is older and more stabilized than the sludge sampled from the walnut shells.

Table 11. Composition of sludge sampled from sludge chambers and media pore-space. Percent C and N are based on TS.

Date	System	Location	TS (g/L)	VS (g/L)	Ash Content	%N	%C
April '13	Small Rock	Pore-space	344.4	84.9	75%	1.3	9.5
April '13	RCA	Pore-space	182.3	69.9	62%	1.6	12.8
April '13	Walnut	Pore-space	77.3	49.2	36%	4.6	33.7

3.1.5 Mass Removal of Nitrogen

With concentration removals and sludge accumulation covered in the preceding sections, nitrogen mass removal can be analyzed. The total nitrogen removed in the effluent for each system (**Table 7**) is removed through nitrification and denitrification as well as deposition in sludge. The average rate of mass nitrogen removal and accumulation from each ReCip system from September 21, 2012 through November 2, 2012 served as a basis for evaluating nitrogen removal performance (**Figure 7**). All systems were run at 2-day HRT and the difference in nitrogen loading rates were due to different hydraulic loading rates into the systems. Mass removal of nitrogen is sensitive to mass loading, and the plastic media had the highest mass loading, which resulted in greater mass removal than the rock and the RCA systems.

Figure 7. Average mass flow of nitrogen in and out of the small ReCip systems during September 21, 2012 through November 2, 2012.

The effluents of the ReCip systems were discharged back into the anaerobic lagoon where further denitrification of the effluent is assumed to have occurred. However, this denitrification is not considered in Figure 7. The total potential nitrogen removal of the ReCip systems with an anaerobic lagoon was assumed to be the complete denitrification of nitrates and nitrites in the ReCip effluent (Kane 2010; Henneman 2011). Because the pilot ReCip systems produced an effluent flow that was minuscule to the volume of the lagoon it is assumed that ReCip effluents did not affect concentrations in the lagoon water. With complete denitrification of ReCip effluent, an additional 9.9 g/d, 8.9 g/d, 18.9 g/d, and 7.4 g/d of nitrogen would be removed from the effluent of the rock, RCA, plastic and walnut shell systems, respectively.

3.1.6 Reciprocation Energy Intensity

Energy intensity is an important factor in choosing treatment technologies, and the energy intensity of reciprocation as a method of aeration has not been characterized previously. The energy consumption of the small systems at Cal Poly cannot be scaled-up reliably due to the small inefficient pumps used. Instead, energy usage values from a commercial-scale ReCip at a swine farm (Stirling Farms, Aliceville, Alabama) were used in the present analysis. The other information needed for the analysis is the oxygen transfer rate due to reciprocation, which was estimated from the small Cal Poly ReCip systems by assessing oxygen demand mass flows.

It was calculated that Stirling Farms ReCip required 0.179 kWh per day per cubic meter of water reciprocated 12 times. To scale-down the Stirling Farms energy intensity to the small Cal Poly systems, the volume of water pumped for each system during reciprocation at Cal Poly was multiplied by the Stirling Farms energy value (**Table 12**).

Table 12. Estimated reciprocation energy use for the small ReCip systems based on 0.179 kWh/m³/d scaled-down from the full-scale Stirling Farms ReCip, which used 12 reciprocation cycles per day. *The plastic media system operated at 24 cycles per day, so a value of 0.358 kWh/m³/d was used.

	Reciprocation Energy (kWh/d)
Rock Media (Small ReCip)	0.035
Recycled Concrete Aggregate	0.035
Vertical Flow Plastic Media*	0.156
Walnut Shell Media	0.057

The estimated oxygen consumption rate was calculated for each system using Equation 6; the consumption rate is assumed to equal the oxygen provision rate of reciprocation (**Table 13**).

Table 13. Oxygen consumption for small ReCip systems inferred from water quality data.

	Oxygen Consumption (kg O ₂ equivalent/d)
Rock Media (Small ReCip)	0.09
Recycled Concrete Agragate	0.09
Vertical Flow Plastic Media	0.39
Walnut Shell Media	0.14

The ratio of reciprocation energy to oxygen consumption gives the aeration or oxygenation energy intensity of each system (**Table 14**). The walnut shells were the most efficient even though they had the second highest water pumping rate after the plastic media, due to the high porosity of the shells. The plastic medium required the most energy due to having the most water to pump to maintain the 2-d HRT and due to having to pump twice as often compared with the other systems.

Table 14. Oxygenation energy intensity for small ReCip systems.

	Oxygenation Energy Intensity (kg O ₂ equivalent/kWh)
Rock Media (Small ReCip)	2.0
Recycled Concrete Aggregate	2.0
Vertical Flow Plastic Media	0.7
Walnut Shell Media	2.2

When compared to standard oxygen transfer rates of mechanical aeration systems, reciprocation in all media, except plastic, was calculated to be more efficient as an aeration mechanism. The Metcalf and Eddy wastewater treatment textbook lists surface low-speed aerators as the most efficient with a transfer rate range of 0.7 – 1.5 kg O₂/kWh, and horizontal rotor aerators as the least efficient with a transfer rate range of 0.5 – 1.1 kg O₂/kWh (Tchobanoglous *et al.* 2003). Future studies should compare energy intensities of trickling filters and biological aerated filters technologies with the energy intensity of the ReCip.

3.2 Large ReCip Analysis

The large ReCip system began operation in January 2010. Starting in October 2011, the hydraulic residence time was decreased from 2.2 days (Starnes 2011) to a 2-day THRT. The system continued to operate at a 2-day THRT through May 2013.

Figure 8. Influent and Effluent TAN concentration and percent removal for large ReCip system operated a 2-day THRT from October 14, 2011 through November 2, 2012.

The experimental period of this thesis (July 20, 2012 through November 2, 2012) comes after 8 months of operation at a 2-day HRT. **Figure 8** is a time series for TAN encompassing the start of 2-day HRT operation to the end of the small ReCip media experiment (October 2011 through November 2012). Over this period, average TAN removal percent was 73% with average influent and effluent TAN concentrations of 208 and 57.8 mg/L. The averaged mass loading rate was 282 kg/ha/d, and the mass removal rate was 204 kg/ha/d. The average TAN mass loading and removal during the

experimental period (**Table 6**) were less than the average loading and removal for the whole 2-day operation.

3.2.1 Sludge Accumulation and Analysis

Solids accumulated in the underdrain chambers on the floor of each system and in the pore spaces of the media. The large ReCip had five underdrain chambers in each basin. Sludge layer thicknesses were measured three times for this thesis in April 2012 before the experiment, October 2012, and April 2013 (**Table 15**). The infrequent measurement minimized disturbance of the sludge layer by sampling. The pore space of the media up to the height of the sludge thickness is assumed to full of sludge.

Table 15. Average sludge thickness in the floor chambers of influent and effluent basis of the large ReCip system for measurement dates associated with the current experiment. Each thickness is the mean of measurements in the 15 chamber standpipes throughout each basin.

Date	Thickness Height (cm)	
	Influent Basin	Effluent Basin
April 2012	10.7	14.6
October 2012	10.8	11.7
April 2013	13.3	15.4

Over the life time of the large ReCip, sludge accumulation was rapid in the first 1.5 years but has increased little since (**Figure 9**), despite higher applied loadings during 2011 through 2012. The occasional decreases in sludge volume are not expected and may be due to sampling error or temporary local migration away from the sampling standpipes. During the current study, sludge was observed draining into the reciprocation sumps during reciprocation. The fill and drain cycles could mobilize sludge, preventing it from building up past a certain thickness in the floor chambers. The overall stabilization of sludge thickness is commonly seen in wastewater treatment systems that accumulate sludge. In wastewater stabilization ponds, as sludge ages it undoes compaction,

consolidation, and degradation resulting in a decreased accumulation rate (Nelson *et al.* 2004).

Figure 9. Sludge accumulation measured by the increase of sludge layer thickness in the chambers of influent and effluent basins of the large ReCip from the start of operation (January 2010) through February 2013.

Pore-space clogging was observed due to the need to shorten reciprocation pumping because there was less water volume in the basins. Previous studies on the large ReCip at the Cal Poly dairy have not measured the sludge accumulation in the media void-space, focusing only on the sludge layer in the chambers. In May 2013 the system's porosity was measured in an attempt to profile sludge accumulation through the media bed (Figure 10).

Figure 10. Porosity profile in large ReCip system from May 2013 measurements. Influent tank was filled while effluent tank was drained. Average porosity was 0.19 for the influent tank and 0.16 for the effluent tank. Original system porosity was 0.49.

Porosity was measured between water elevations. Water elevation measurements were taken while the influent tank was filled and the effluent tank was drained. The effluent tank mead bed was better profiled because the change from the first to the second water elevation in the influent tank reaches the chamber level at 0.36 m. Because this was the first measurement of void-space reduction due to sludge accumulation for this system more studies are needed to better determine accumulation rates, and sludge distribution across the tank and through the media.

Sludge samples from the ReCip systems were analyzed for total and volatile solids content (TS and VS), as well as carbon and nitrogen content (**Table 16**). The sludge trapped in the pore-space had much higher solids and ash content than sludge in the chamber. The sludge in the pore space could have a higher degradation rate than the

sludge in the chambers because it is exposed to the atmosphere when a basin is drained during reciprocation.

Table 16. Sludge composition from chamber and pore-space in large ReCip.

Date	System	Location	TS (g/L)	VS (g/L)	Ash Content	%N	%C
October 2012	Large ReCip	Sludge Chamber	34	16	54%	3.503	27.16
April 2013	Large ReCip	Sludge Chamber	20			2.866	21.41
April 2013	Large ReCip	Pore-space	422	82	81%	2.367	16.89

3.3 Comparison of Large and Small Rock Aggregate Systems

The small ReCip system with rock media was constructed to have similar physical characteristics as the large ReCip, so systems of different sizes and ages could be compared. The layers of rock aggregate were the same in both systems, but the overall clean bed porosity of the large ReCip is slightly larger due to having more floor chamber volume per tank volume. It is expected that the older system with less basin water volume would perform worse than the new system due to having shorter actual residence time for treatment. Graphical analysis of water quality data and comparison of average effluent concentrations were used to compare the small and large ReCip systems (**Figure 11 – 14**).

Figure 11. Time-series effluent $CBOD_5$ concentrations of rock media ReCip systems. Averaged concentrations for the small and large ReCip was the same (155 mg/L) for experimental period (July 20 - November 2).

Figure 12. Time-series effluent TAN concentrations of rock media ReCip systems. Averaged concentrations for the small and large systems was the same (37.0 mg/L) for the experimental period (July 20 - November 2).

Figure 13. Time-series of total suspended solids (TSS) concentrations for rock media ReCip systems. Averaged values for small and large ReCip were 0.66 and 0.70 g/L for the experimental period (July 20 - November 2). The difference in effluent concentrations was not significant enough to conclude that it was caused by system size or age.

Figure 14. Time-series effluent total nitrogen (TN) concentrations for rock media ReCip systems. The significant difference in effluent concentrations between small and large ReCip systems before September 21 is attributed to poor nitrate removal during startup of the small system. During pseudo-steady state operation (September 21 – November 2), averaged values for small and large ReCip systems were 120 and 118 mg/L.

No significant differences in effluent concentrations for the main water quality parameters – TSS, CBOD5, and TAN – were observed between the small and large ReCip systems; the observed difference in TN during until September 21 was attributed to poor nitrate removal due to establishment of media in the small system. System size and age did not impact effluent concentrations and treatment performance. Although the media in the large systems was clogged with sludge (**Table 17**), the reduced water volume – and lower actual residence time – did not affect treatment performance. Organic loading has a greater influence on treatment performance than residence time. Further studies are necessary to assess the effect of long term clogging on treatment to find when the reactor should be cleaned of sludge. Future ReCip studies and designs should treat organic loading into the system as the major operational design parameter.

CHAPTER 4

Conclusions

The ReCip biofilter pilot systems described in the present thesis successfully removed nitrogen and organic matter from freestall barn flushwater at the Cal Poly Dairy. The main treatment mechanisms typically seen in ReCip systems are nitrification-denitrification, organic matter oxidation, and the capture of both nitrogen and carbon in sludge that becomes trapped in the ReCip medium (Henneman 2011).

Two main studies were conducted during the thesis research: First, different biofilm media were tested and compared in terms of treatment performance and, second, the long-term performance of a ReCip in continuous operation for 3 years was characterized. All five pilot systems were operated with the same hydraulic residence time, based on liquid volume in the pores. Thus, the flow rate through the units with more porous media was greater than that received by the lower porosity units.

The metrics for judging treatment performance were removal of total nitrogen, total ammonia nitrogen, and oxygen demand. Removal of these three constituents was compared in terms of concentration, mass per time based on overall tank volume; mass per time on hectore scale basis; nitrogen was also analyzed as mass per time per area of media surface. Additional denitrification of nitrate in the effluent discharged to the anaerobic lagoon is considered, but for the purpose of comparison between systems the TN removal was considered the difference between influent and effluent concentrations of the systems. The sludge accumulation rate within the systems was the main operational metric considered because sludge clean-out is likely to be costly for ReCip systems. In

addition to sludge volumes in the plastic chambers, sludge occupying media pore space was calculated by measuring the change in porosity in each system.

4.1 Treatment Substrate Comparison

Four 2.67-m² ReCip systems, each with a different physical substrate – rock aggregate, recycled concrete aggregate (RCA), biotower vertical-flow plastic media, and broken walnut shells – were operated at a 2-day theoretical retention time (THRT) over the course of a 16-week study. Rock aggregate is the substrate traditionally used in ReCip systems, each medium was tested to compare concentration removal efficiencies, mass removal rates, and system energy based on oxygen utilization, but all four media were found to be functional for ReCip systems.

The walnut shell substrate emerged as the most effective for total nitrogen removal out of the effluent at 69% reduction in concentration equating to 54.4 g/d and total nitrogen retained in sludge was 5.6 g/d (276 kg/ha/d in the effluent) (**Table 7 and Figure 7**). The removals of TAN and CBOD₅ by the walnut shell system were the greatest of the substrates tested at 94% and 68%, respectively. The walnut substrate achieved the greatest oxygenation energy efficiency at 2.2 kg O₂ equivalent/kWh and the second greatest in terms of nitrogen removal per substrate surface area at 176 mg/m²/day. This study was apparently its second use as a physical medium in a biological wastewater treatment device, the first being a reciprocating anaerobic filters at the Cal Poly Dairy, in 2012.

A major concern with the walnut shells as a medium was the rate of sludge accumulation in the medium; pore volume decreased by 30% in 5 months and 39% in 9 months. Although the porosity of the shell bed decreased substantially, treatment

performance did not decrease. This substrate was the best at removing solids from the wastewater and had a 50% TSS removal overall. A longer study is needed to determine when sludge accumulation negatively affects treatment performance or operation. The insensitivity of treatment performance to sludge accumulation might indicate that biofilm surface area was not the limiting factor in treatment, with the main possibility for limitation being oxygen supply (a function of reciprocation frequency).

The plastic medium achieved the second greatest mass removal per time, outperforming the rock and RCA substrates at 35.3 g/d (172 kg/ha/d) TN at a 2-day THRT. Despite high mass removal rates, this substrate provided the lowest concentration decrease of the substrates; the vertical-flow plastic media would not be recommended for use in ReCip systems meant to meet low concentration discharge limits. However, for systems meant to have high nitrogen mass removal rates, plastic media would be an appropriate alternative, although one with a relatively high cost. The plastic medium required the most pumping because it had the largest wetted volume of the media. Twice as many reciprocations were needed to keep biofilm wet, leading to the highest oxygenation energy intensity of the systems at 0.7 kg O₂ equivalent/kWh.

For nutrient management at dairies, one goal is to have a high nitrogen mass removal rate. Thus, the plastic medium is still a feasible substrate for ReCip systems. Besides good nitrogen mass removal rate, a major advantage of the plastic medium over the others is that it will take much longer to clog with sludge due to its large vertical channels. However, the plastic medium was the most expensive media, so additional study at higher loading rates is recommended as well as an economic analysis of media costs versus sludge cleanout costs.

The recycled concrete aggregate medium achieved removal efficiencies in between that of the walnut shells and the rock aggregate. The better treatment by the RCA than by the rocks may be its higher surface area, 516 m² in the RCA systems while the rock system had a total media surface area of 243 m². The TN removal per media surface area for RCA was 57 mg/m²/d, whereas for rock aggregate, it was 102 mg/m²/d; the RCA may not be a better material for biofilm growth than rock, but its greater surface area led to better treatment overall. Because the RCA aggregate granules were smaller than the natural rocks, the RCA medium experienced greater sludge accumulation though it only accounts for minimal amount of removal. The RCA was also the second most efficient at

The rock aggregate, although outperformed by the alternate media in terms of mass removal, is a functional media for ReCip systems. CBOD₅ removal percentage was 50% with a mass removal rate of 112 kg/ha/d. TN removal percentage was 43% and its mass removal rate was 103 kg/ha/d. The system had oxygenation energy intensity of 2.0 kg O₂ equivalent/kWh, the same efficiency as the RCA system and greater than the standard oxygen transfer rate of mechanic aeration.

4.2 Large ReCip System Operation

The large ReCip system has been in continuous operation for 3 years. The system was run at a 2-day HRT starting in October 2011 and through the present study (July 20, 2012 – November 2, 2012). Running 2-day HRT the system was less efficient at treatment than previous operations of the system at a 2.2-day HRT (Starnes 2011). It is expected that efficiency will decrease with decrease in residence time – really increase in

hydraulic loading – but mass removal seems to respond to an increase or decrease in organic loading.

4.3 Large and Small ReCip Comparison

Comparison of effluent water quality between the small and large ReCip systems using a rock aggregate physical substrate has concluded that size and age of the system are not factors in treatment performance. The large system was clogged with sludge leading to reduced actual residence times for the same hydraulic loads. Because no significant difference in treatment was observed, organic loading is the major parameter for treatment performance and should be considered over hydraulic residence times in future ReCip designs.

4.4 Future Research

Although three-years of data are now available for the ReCip technology at the Cal Poly dairy, and equations and removal rates relevant to design have been formulated (Kane 2010, Henneman 2011, Starnes 2011) and in Sections 3.1 and 3.2 of this thesis, only hydraulic residence time and reciprocation frequency have been studied. The ReCip has an unusual hydraulic regime since wastewater is pumped back and forth, not simply recirculated. For example, the relative timing of the influent pulses and the reciprocation may influence results. More detailed hydraulic studies of the ReCip would help with modeling retention times and removal rates.

Sludge accumulation profiling is also necessary to understand the movement of solids in the biofilter. If more media studies are conducted, it should focus on activity and growth of the biofilm on the media as well as sludge contribution to treatment performance. NVS/VS ratio in the influent vs. in the sludge should be considered to

estimate how much sludge was captured and then degraded in the various media similar to method for VS destruction calculation in the M&E digester chapter.

Further studies on reciprocation as an aeration mechanism would help promote ReCip systems. Bisulfite testing or other rigorous aeration testing should be conducted in a future study. The oxygen energy intensity should also be compared with activated sludge systems, trickling filters and biological aerated filters.

Bibliography

APAH (2005). *Standard Methods for the Examination of Water and Wastewater*, American Public Health Association, Water Environment Federation, and American Water Works Association.

Behrends, L. L. (1999). *U.S. Patent No. 5,863,433*. Washington, DC: U.S. Patent and Trademark Office.

Behrends, L. L. (2009). ReCip Wastewater Technologies: Effects of Substrate Types and System Configurations. *Proceedings of the Water Environment Federation*, 2009(15), 2191-2202.

Behrends, L., Bailey, E., Ellison, W., Houke, L., Jansen, P., Shea, C., Smith, S., & Yost, T. (2002) Reciprocating Constructed Wetlands for Treating High Strength Anaerobic Lagoon Wastewater. Department of Air, Land and Water Sciences, Tennessee Valley Authority, CEB 1-C, Muscle Shoals, AL

Cohen, Y. (2001). Biofiltration—the treatment of fluids by microorganisms immobilized into the filter bedding material: a review. *Bioresource technology*, 77(3), 257-274.

Crites, R. W., Middlebrooks, E. J., & Reed, S. C. (2010). *Natural wastewater treatment systems*. CRC Press.

Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J., & Tchobanoglous, G. (2005). *MWH's Water Treatment: Principles and Design: Second Edition*. Wiley.

Green, F. B., Lundquist, T. J., & Oswald, W. J. (1995). Energetics of advanced integrated wastewater pond systems. *Water Science & Technology*, 31(12), 9-20.

Henneman, S. (2011). Water and Air Quality Performance of a Reciprocating Biofilter Treating Dairy Wastewater. MS Thesis, Civil and Environmental Engineering Department, California Polytechnic State University, San Luis Obispo.

Kadlec, R. H., & Wallace, S. (2008). *Treatment wetlands*. CRC press.

Kane, J. P. (2010). Water quality performance of a reciprocating biofilm reactor for treatment of dairy wastewater. MS Thesis, Civil and Environmental Engineering Department, California Polytechnic State University, San Luis Obispo.

Leonard, K. M., & Cunningham, A. L. (2000, July). Comparison of Gravity-Flow and Reciprocating Constructed Wetland Performance. In *Environmental and Pipeline Engineering 2000* (pp. 9-15). ASCE.

Nelson, K. L., Cisneros, B. J., Tchobanoglous, G., & Darby, J. L. (2004). Sludge accumulation, characteristics, and pathogen inactivation in four primary waste stabilization ponds in central Mexico. *Water Research*, 38(1), 111-127.

Ragusa, S. R., McNevin, D., Qasem, S., & Mitchell, C. (2004). Indicators of biofilm development and activity in constructed wetlands microcosms. *Water Research*, 38(12), 2865-2873.

Rice, M., Humenik, F., (2004). Solids Separation-Reciprocating Wetland. North Carolina State University.

Starnes, J. C. (2011) Treatment of Dairy Anaerobic Lagoon Water Using Reciprocating Subsurface Flow Biofilm Reactors – Performance Review Under Hydraulic Loading. MS Thesis, University of Stuttgart, Germany.

Tchobanoglous, F.L. Burton, and H.D. Stensel (2003). “Wastewater Engineering Treatment and Reuse,” Metcalf & Eddy, Inc. McGraw Hill.

Appendices

Appendix A: Detailed Methods

Suspend Solids

APHA Method 2540 D and E were followed in the analysis of total suspended solids (TSS) and volatile suspended solids (VSS), respectively. Samples were filtered through prewashed and ashed 1.2 μm G4 glass fiber filters (Fisher Scientific). Laboratory triplicates were used for quality control.

Biochemical Oxygen Demand (BOD₅)

APHA Method 5210 B was followed in the analysis of carbonaceous and soluble carbonaceous 5-day biochemical oxygen demand. Dilution water was Grade 1 deionized water (DI) and prepared with Hach BOD Nutrient Buffer Pillows. Hach Nitrification Inhibitor Formula 2533 was added to each bottle except blanks or standards. Two blanks and two standards were prepared for each batch of samples. Lastly, one split with a different dilution was prepared for each sample. Soluble samples were centrifuged at 13500 rpm for 10 minutes and then filtered through a .45 μm filter before added to the BOD bottle.

Total Ammonia Nitrogen

APHA Method 4500-NH₃ D was followed in the analysis of total ammoniacal nitrogen using an Orion 9512 Ammonia-selective electrode. Four point calibration curves, using 1, 10, 100 and 1000 mg/L NH₃ standards was used for calibration as suggested by Standard Methods. Matrix spikes and splits were used for quality control.

Nitrate

APHA 4500-NO₃⁻ D was followed in analysis of nitrate as nitrogen using Thermo Scientific Orion 9700BNWP Nitrate-selective electrode. Four point calibration curves, using 1, 10, 100 and 1000 mg/L NO₃-N standards was used for calibration. Matrix spikes and splits were used for quality control.

Nitrite

APHA 4500-NO₂⁻ B was followed in analysis of nitrite as nitrogen. Samples were centrifuged at 13500 rpm for 10 minutes to ease filtering of samples. Samples were then filtered through a 45 µm filter. Samples were diluted to reduce color interference and to be within acceptable ranges for this analysis. Four point calibration curves, using 0.1, 0.2, .03, and 0.4 mg/L NO₂-N was used. Spectrophotometer used for analysis was Shimadzu UV Parma Spec UV-VIS spectrophotometer. Matrix spike and splits were used for quality control.

Total Kjeldahl Nitrogen

APHA 4500-N_{org} B was followed in analysis of total Kjeldahl nitrogen. A sample volume of 10mL was used for influent samples and 25mL was used for effluent samples. A 2500ppm as NH₃ stock ammonia standard was used to create 20.58ppm as N and 41.17ppm as N check standards. Matrix spikes and splits were used for sample quality control.

Appendix B: Follow-up ReCip Experiment

A follow-up experiment was performed with the assistance of Cal Poly Civil and Environmental Engineering undergraduate students Cameron Koizumi, Robert Kroner, and Aaron Carriedo during January and February of 2013. The purpose of the experiment was to monitor nitrogen removal while changing the treatment parameters of the systems. The experimental parameters were:

- Keep the large ReCip at the same operation parameters to be used as a control.
- Adjust the reciprocation cycles of the small rock and RCA system to observe effect on nitrogen removal.
- Adjust the loading rates of walnut and plastic systems.

The reciprocation cycles on the rock system was set to 8, 3 hour period per day; the RCA system was set to 4, 6 hour cycles per day. The pump periods remained around 20 minutes. The flow rate in the walnut shell system was doubled so that it operated at a 1 day residence time. The flow rate for the plastic media system was halved so that it operated at a 4 day residence time. The ReCip systems were offline in December 2012, so there was a two week startup period in January 2013. Samples were taken once a week on Fridays at 8:30 in the morning. System maintenance was performed on Saturdays and influent pump times were adjusted on Tuesdays to maintain consistent hydraulic loading rates to the systems. Most laboratory analysis was performed on Fridays after samples were taken with the exception of total Kjeldahl nitrogen, which was analyzed on Thursdays the week after the samples were taken.

The data set includes nitrogen analysis from five samples dates from January 2013 through February 2013. The average concentrations obtained from laboratory analysis is presented in **Table 17**. Average nitrogen removal efficiency for each system is presented in **Table 18**.

Table 17. Average concentration of nitrogen water quality analysis for January through February 2013

Reactor	TAN mg/L-N	Nitrate mg/L-N	Nitrite mg/L-N	TKN mg/L-N	ON mg/L-N	TN mg/L-N
Influent	194.14	28.61	0.03	309.54	115.40	338.18
Large ReCip Rock	56.90	38.15	0.87	164.81	107.91	203.83
Small ReCip Rock	56.70	27.37	2.35	163.02	106.31	192.73
RCA	25.33	29.61	1.13	128.74	103.42	159.49
Vertical Flow Plastic Media	78.41	33.99	1.57	187.66	109.25	223.22
Walnut Shells	25.71	30.10	0.98	124.38	98.67	155.46

Table 18. Average removal efficiencies

Reactor	TAN	TKN	Organic N	Total N
Large ReCip Rock	70.7%	46.8%	6.5%	39.7%
Small ReCip Rock	70.8%	47.3%	7.9%	43.0%
RCA	87.0%	58.4%	10.4%	52.8%
Vertical Flow Plastic Media	59.6%	39.4%	5.3%	34.0%
Walnut Shells	86.8%	59.8%	14.5%	54.0%

The TAN removal also represents nitrification efficiency. Since nitrate is created as ammonia in nitrified, the combined theoretical available nitrate for denitrification must be used to calculate denitrification efficiency. The nitrate and nitrite measured in the effluent constitutes the amount of nitrogen not denitrified by the ReCip systems. The denitrification efficiencies are presented in **Table 19**.

Table 19. Average denitrification efficiency of ReCip systems

Reactor	Nitrate available (mg/L-N)	Nitrite available (mg/L-N)	Effluent Nitrate plus Nitrite (mg/L-N)	Denitrification Efficiency
Large ReCip Rock	165.86	0.03	39.02	76%
Small ReCip Rock	166.06	0.03	29.72	82%
RCA	197.43	0.03	30.74	84%
Vertical Flow Plastic Media	144.35	0.03	35.56	75%
Walnut Shells	197.05	0.03	31.08	84%

Changing the flow rates in the vertical flow plastic media and walnut shell systems changed the removal efficiencies of each system compared to analysis performed

from September through November 2012. The plastic media was the had the worst concentration removal efficiencies of all the media tested while receiving the largest influent loading rate, so the flow rate was halved increasing the residence time from 2 days to 4 days. A slight improvement in nitrogen removal efficiency was observed. The reduced flow rate was still greater than the RCA and rock aggregate systems received. The walnut shell system doubled in flow rate such that the residence time increased from 2 days to 1 day. A slight decrease in treatment efficiency was observed, but the walnut shells remained the most efficient of all the media tested.

Adjusting the reciprocation rate changes the amount of aeration the ReCip receives. The small and large rock aggregate systems can be compared directly. The small ReCip system received two thirds the amount of aeration as the large system, but resulted in similar nitrogen removal. The RCA system received half the aeration compared to the experiment run in September 2012, but no significant reduction in ammonia removal and total nitrogen removal was observed when comparing the results from each experiment. For dairy wastewater systems, a lower reciprocation rate would lead to less energy usage. The effects of reciprocation rates should be the subject of further study.