Protecting Our Water Environment

Metropolitan Water Reclamation District of Greater Chicago

MONITORING AND RESEARCH DEPARTMENT

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DEVELOPMENT OF A SCALABLE, FLOW-THROUGH ALGAL WASTEWATER TREATMENT SYSTEM FOR SUSTAINABLE NUTRIENT REMOVAL AT THE TERRENCE J. O'BRIEN WATER RECLAMATION PLANT

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DEVELOPMENT OF A SCALABLE, FLOW-THROUGH ALGAL WASTEWATER TREATMENT SYSTEM FOR SUSTAINABLE NUTRIENT REMOVAL AT THE TERRENCE J. O'BRIEN WATER RECLAMATION PLANT

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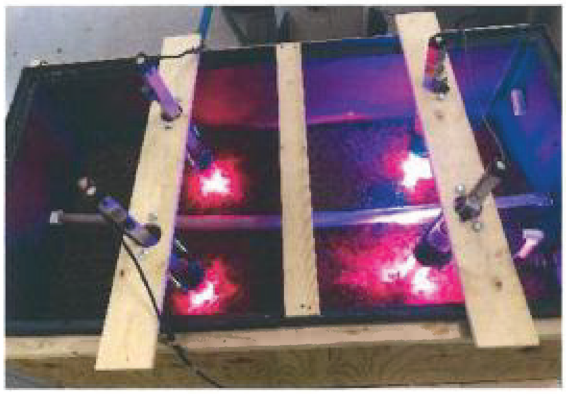

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ACRONYM LIST

Acronym	Definition
AACE	American Association of Cost Engineers
C	carbon
CO_2	carbon dioxide
COD	chemical oxygen demand
CREE	Center for Research in Education and the Environment
District	Metropolitan Water Reclamation District of Greater Chicago
EIA	environmental impact assessment
EPS	extracellular polymers
HPDE	high density polyethylene
HRT	hydraulic retention time
LCA	life-cycle analysis
LPH	liter per hour
MBBR	moving bed biofilm reactor
MGD	millions of gallons per day
ms	milli seconds
N	nitrogen
NREL	National Renewable Energy Laboratory
NH_3-N	Ammonia-nitrogen
NO_3-N	Nitrate Nitrogen
O_2	oxygen
O&M	operating and maintenance
PAO	phosphorus accumulating organisms
PO_4-P	orthophosphate
SRT	solids retention time
TEA	techno-economic analysis
TSS	total suspended solids
TN	total nitrogen
TP	total phosphorus
UCSD	Urbana-Champaign Sanitary District
USEPA	United States Environmental Protection Agency
WRP	water reclamation plant
WRF	Water Research Foundation
WWTP	wastewater treatment plant

EXECUTIVE SUMMARY

The State of Illinois has adopted a nutrient loss reduction strategy and set goals to reduce its Phosphorus (P) load by 25 percent and its Nitrogen (N) load by 15 percent by 2025. In response to this initiative, the Metropolitan Water Reclamation District of Greater Chicago (District) is collaborating with the Illinois Sustainable Technology Center at the University of Illinois to develop a scalable algal wastewater treatment system for enhanced nutrient removal and the potential for beneficial reuse of algal biomass. For this project, a set of four bench-scale, fixed-film algal wastewater treatment systems with LED lighting was designed, built, and operated to investigate and optimize system performance, with enhanced phosphorus removal as the primary treatment goal. The LED lighting allows more light per surface area to be delivered to the algal growing system than typical solar-lighted systems, which facilitated the use of deeper tanks and a significantly smaller process footprint. The use of the attached fixed-film algal biomass made it possible to separate the hydraulic retention time (HRT) and the solids retention time (SRT) of the algal biomass, which allowed use of a much smaller HRT without flushing out the algal biomass. Routine biomass harvesting by air scour of the attached growth media was also demonstrated. Most of the sloughed biomass was well flocculated into relatively dense biofilm fragments that could be quickly separated from the bulk liquid flow by sedimentation. However, the reactors also supported growth of some suspended algae and bacteria that required several hours of settling to be harvested from the liquid flow.

A series of experiments were conducted using the secondary effluent from the Urbana-Champaign Sanitary District (UCSD) as influent to the bench-scale, LED-lighted, fixed-film algae wastewater treatment reactors constructed for this project. These experiments were designed to optimize reactor performance and compared four different types of biofilm growth media: (1) no media (control), (2) plastic media only, (3) plastic media with algae gel coating, and (4) plastic media with adsorbent and algae gel coating. The performance of the system with integrated adsorbents and algae was better than the others, with the largest differences occurring near the beginning of operations. After optimization to minimize HRT, the system with integrated adsorbents was able to remove more than 60 percent of reactive P from the influent with a six-hour HRT. On a concentration basis, the six-hour HRT removed 1.2 mg/L of reactive or ortho-P on average, and effluent reactive phosphorus concentration was below 0.5 mg/L. Higher P removal percentages can be achieved with longer HRTs, but this increases the unit cost of P removal. Similar trends were also observed in NO_3-N removal. The system with adsorbent and algae-coated K5 media had the lowest NO_3-N concentration in effluent. In general, the percent removal of N was lower than for P.

The effect of adding carbon dioxide (CO_2) into the air feed used for mixing in the algae bioreactors was also evaluated during this study. The CO_2 concentrations between 0.5 percent and eight percent (v/v basis) were tested, and optimum performance was observed between 1 - 2 percent (v/v), which lowered effluent P to 0.25 mg/L and increased the total P removal by approximately 10 percent. If the effluent P treatment goal is held at 0.5 mg/L, then there is some room for further optimization to reduce the HRT below six hours, but this refinement was not tested. Also, it is noteworthy that recycling excess CO_2 from other existing wastewater process off-gases can reduce net greenhouse gas emissions.

Optimization of the electrical inputs for LED lighting was conducted by reducing the light intensity and adding rapid flashing of the LED lights, which is known to improve algal photosynthetic efficiency. Overall, a photosynthetic efficiency of 16 percent was achieved when the lighting condition was 720 $\mu mol/m^2$-s with flashing at 100Hz. This is significantly higher than the typical photosynthetic efficiency of a solar-lighted algae systems, which is <5 percent. However, there is still some potential for further optimization of photosynthetic efficiency, with theoretical limits typically estimated to be in the range of 25 - 35 percent.

The fixed-film algal growth was also accompanied by growth of suspended algae and bacteria that increased the total suspended solids (TSS) in the effluent of the algal treatment system above the influent levels. This suspended biomass required six hours of settling time to achieve TSS below 10 mg/L without flocculation, or four hours with autoflocculation induced by increasing the pH to ten. For this study, we also evaluated other approaches to remove the suspended biomass and determined that cloth filtration would provide a better alternative because of better effluent water quality, a smaller process footprint, and lower system costs. Cloth filters have been demonstrated to remove algae in some other applications, but they were not specifically tested with the mixed algal-bacterial biomass produced in this study.

Techno-economic analysis (TEA) was conducted for a 100 MGD sizing of the proposed algal treatment system using a baseline design condition of performance parameters demonstrated during this study. In addition, the TEA evaluated an advanced design condition that includes several improvements to the baseline system that are considered readily achievable in the near term without any major technological breakthrough. In particular, the advanced design condition includes the United States Department of Energy-projected decreases in LED production costs and the use of cloth filters for suspended biomass removal. Although other technological improvements are likely given the current level of interest and research in algal biotechnology, these were considered too speculative for quantification and were not included in the TEA. However, the TEA did evaluate the potential economic impacts of selling the algal biomass for animal feed. Animal feed has a somewhat higher value than biofuel feedstocks, but it is still a large-market commodity product with stable pricing that would not be significantly affected by the entry of new sources.

The breakdown of estimated system costs for the baseline and advanced design conditions are summarized in Table ES-1 and ES-2, respectively. Near the top of these tables, the total cost of P removal ($/lb P) is provided for four cases: (a) Whole Plant without product revenue, (b) Whole Plant with product revenue, (c) Expansion Unit without product revenue, and (d) Expansion Unit with product revenue. The "Expansion Unit" cases consider the cost to add an algal treatment system to the end of an existing wastewater plant process and divide by the amount of P removed in the expansion unit only. The "Whole Plant" cases use the same cost as the algae treatment expansion cases but divide that cost by the total P removal occurring in the whole plant. The "Whole Plant" cases were calculated because many of the past studies on advanced wastewater nutrient removal used this approach, which allows a direct comparison with a broader variety of previous studies and alternative treatment processes. In addition, the expense of removing nutrients generally increases as the effluent level decreases. Thus, the cost of adding a new P removal process at the end of a treatment plant can be unfairly biased upward unless all options use the

TABLE ES-1: SUMMARY OF TECHNO-ECONOMIC DATA FOR A 100 MGD LED-ENHANCED, FIXED-FILM ALGAL NUTRIENT REMOVAL SYSTEM UNDER THE BASELINE DESIGN CONDITION

Phosphorus Removal Unit Cost for LED Enhanced Fixed-Film Algal Nutrient Removal System

100 MGD, Baseline Case

P Removal Unit Cost (Whole Plant)	14.75	$/lb-P
P Removal Unit Cost (Whole Plant) with product revenue	12.03	$/lb-P
P Removal Unit Cost (Expansion Unit)	85.38	$/lb-P
P Removal Unit Cost (Expansion Unit) with product revenue	68.33	$/lb-P

Plant performance		
Plant Flow	100	MGD
Plant Influent TP	6	mg/L
Plant Effluent TP	0.5	mg/L

System performance		
Biomass Poduction	4200	Ton/yr
P Removal (Whole Plant)	763	Ton/yr
P Removal (Expansion unit)	208	Ton/yr

Expansion Capital Cost		% of Process
LED Enhanced P Removal Reactor		
Main Tank (clarifier[†] @ 6 hour HRT)	$ 28,217,000	16%
LED Strip	$ 77,760,000	45%
LED Power Supply and Controls	$ 6,480,000	4%
LED Glass tube and Cooling	$ 10,800,000	6%
Feed Pump	$ 1,901,000	1%
Media	$ 9,500,000	6%
Blower	$ 10,857,000	6%
TSS Removal - Autofloculation		
Clarifier [#] @ 4h HRT)	$ 22,574,000	13%
Sodium Hydroxide Feed (50%)	$ 267,000	0.2%
Biomass Dewatering		
Filter Press (to 20% solid content)	$ 83,000	0.05%
Drum Dryer	$ 2,503,000	1%
Sub Total Process Cost	$ 171,015,000	100%
Yard Piping (10%)	$ 17,102,000	
Sitework Landscaping (5%)	$ 8,551,000	
Site Electrical & Control (20%)	$ 34,203,000	
Total Construction Cost	$ 230,871,000	
Engineering , Legal, Adminstratiive Cost (35%)	$ 80,805,000	
Total Capital Cost	$ 311,675,000	

Expansion O&M Cost		% of O&M cost
Labor Cost		
Operation/Maintanence Labor	$ 689,000	4%
Operation Supervisor	$ 65,000	0.3%
Labor Benefits (30%)	$ 226,000	1%
Sub-Total Labor Cost	$ 980,000	
Reagent Usage		
Sodium Hydroxide Feed (50%)	$ 418,000	2%
Sulfuric Acid Feed (93%)	$ 943,000	5%
Sub-Total Reagent Cost	$ 1,361,000	
Maintenance		
Routine Maintenance	$ 2,309,000	12%
Capital Replacement	$ 3,463,000	18%
Sub-Total Maintenance Cost	$ 5,772,000	
System Energy		
Electric Power - LED	$ 8,162,000	44%
Electric Power - Aeration	$ 2,335,000	12%
Electric Power - Filter Press	$ 7,000	0.04%
Nature Gas for Drying	$ 125,000	1%
Sub-Total Energy Cost	$ 10,630,000	
Total Annual O&M Cost	$ 18,743,000	100%
WWTP Energy Cost Allocated to P removal	$ 1,674,000	

Interest Rate	4%
Term (year)	20

[†] Ten units of 35,000 ft^2 (10 ft depth); [#] 8 units of 35,000 ft^2 (10 ft depth).

TABLE ES-2: SUMMARY OF ECONOMICS FOR A 100 MGD LED-ENHANCED, FIXED-FILM ALGAL NUTRIENT REMOVAL SYSTEM UNDER THE ADVANCED DESIGN CONDITION

Phosphorus Removal Unit Cost for LED Enhanced Fixed-Film Algal Nutrient Removal System

100 MGD, Advanced Case

P Removal Unit Cost (Whole Plant)	8.59	$/lb-P
P Removal Unit Cost (Whole Plant) with product revenue	5.86	$/lb-P
P Removal Unit Cost (Expansion Unit)	45.08	$/lb-P
P Removal Unit Cost (Expansion Unit) with product revenue	28.04	$/lb-P

Plant performance			**System performance**		
Plant Flow	100	MGD	Biomass Poduction	4200	Ton/yr
Plant Influent TP	6	mg/L	P Removal (Whole Plant)	763	Ton/yr
Plant Effluent TP	0.5	mg/L	P Removal (Expansion unit)	208	Ton/yr

Expansion Capital Cost		% of Process
LED Enhanced P Removal Reactor		
Main Tank (clarifier[†] @ 6 hour HRT)	$ 28,217,000	30%
LED Strip	$ 16,070,000	17%
LED Power Supply and Controls	$ 4,018,000	4%
LED Glass tube and Cooling	$ 6,696,000	7%
Feed Pump	$ 1,901,000	2%
Media	$ 9,500,000	10%
Blower	$ 10,857,000	12%
TSS Removal - Cloth Filteration		
Cloth Filter[#]	$ 13,000,000	14%
Filter house	$ 600,000	0.6%
Biomass Dewatering		
Filter Press (to 20% solid content)	$ 83,000	0.09%
Drum Dryer	$ 2,503,000	3%
Sub Total Process Cost	$ 93,445,000	100%
Yard Piping (10%)	$ 9,345,000	
Sitework Landscaping (5%)	$ 4,672,000	
Site Electrical & Control (20%)	$ 18,689,000	
Total Construction Cost	$ 126,151,000	
Engineering , Legal, Adminstratiive Cost (35%)	$ 44,153,000	
Total Capital Cost	$ 170,304,000	
Interest Rate	4%	
Term (year)	20	

Expansion O&M Cost		% of O&M cost
Labor Cost		
Operation/Maintanence Labor	$ 689,000	7%
Operation Supervisor	$ 65,000	1%
Labor Benefits (30%)	$ 226,000	2%
Sub-Total Labor Cost	$ 980,000	10%
Maintenance		
Routine Maintenance	$ 1,241,000	13%
Capital Replacement	$ 1,241,000	13%
Sub-Total Maintenance Cost	$ 2,482,000	26%
System Energy		
Electric Power - LED	$ 3,652,000	38%
Electric Power - Aeration	$ 2,335,000	24%
Electric Power - Filter Press	$ 7,000	0%
Nature Gas for Drying	$ 125,000	1%
Sub-Total Energy Cost	$ 6,119,000	
Total Annual O&M Cost	$ 9,681,000	100%
WWTP Energy Cost Allocated to P removal	$ 1,674,000	

[†] Ten units of 35,000 ft^2 (10 ft depth); [#] 14 Aqua MegaDisk Cloth Filter Units.

same influent concentration. Looking at Table ES-1, the Whole-Plant Baseline Design P removal unit cost is $14.75/lb-P without product revenue and $12.03/lb-P with revenue for animal feed. Table ES-2 shows that for the Whole Plant-Advanced Design case, the projected cost of P removal would be reduced to $8.59/lb-P without any product revenue or $5.86/lb-P if animal feed product revenue is included. These projected unit costs for the proposed algal treatment system design are competitive with a broad survey of other currently available nutrient removal processes, which had costs ranging from $2.50 - $12.02/lb-P and an average cost of $7.5/lb-P removed. Finally, Appendix A provides a preliminary design for an upscale pilot algal treatment system to demonstrate the scalability of the process and further optimize key operating parameters.

PROJECT DESCRIPTION

The increasing use of N and P in industry and agriculture, as well as increased dietary protein consumption, has led to greater loading of N and P nutrients to municipal wastewater and to the aquatic environment. Elevated nutrient levels can contribute to undesirable environmental conditions, such as eutrophication and hypoxia, as excess N and P from municipal wastewater, industries, fertilizer, and animal manure eventually enter surface waters. Wastewater treatment plants (WWTP) can be significant contributors to the nutrient levels in surface waters and aquatic ecosystems. For instance, it is estimated that as much as 70 percent of the P-loading in the Upper Illinois River Basin and approximately 5 percent of P-loading in the Mississippi River Basin can be attributed to the effluent from a handful of large water reclamation plants (WRPs) in the Chicago metropolitan area (David and Gentry, 2000; Bedore et al., 2008).

To help address the nutrient issues, a regional task force for the Mississippi River Basin created an action plan with goals for reducing the total N and P-loading by 45 percent in an effort to reduce the size of the Gulf hypoxic zone (Mississippi River/Gulf of Mexico Watershed Nutrient Taskforce, 2008). Individual states have also been increasing efforts to reduce nutrient pollution. For instance, the state of Illinois has recently adopted a nutrient loss reduction strategy, which affirms the eventual target of a 45 percent reduction in nutrient loadings to the Mississippi River and describes a suite of best management practices for reducing loads from wastewater plants, urban runoff, and agricultural runoff. By 2025, these practices are intended to help the state reduce its P load by 25 percent and its N load by 15 percent. To achieve the desired goals for reduced nutrients in the aqueous environment, there is increasing pressure on the agricultural industry to reduce non-point sources of nutrients, and stricter effluent nutrient limits are being imposed on point sources, including WRPs in the Mississippi River Basin. In particular, WRPs are more frequently being required to reduce P levels in their discharges.

The District operates seven WRPs in Cook County and serves a population equivalent to 10.35 million, which includes 5.25 million people, a commercial/industrial flow equivalent to 4.5 million people, and a combined sewer overflow equivalent to 0.6 million people. Past District reports quantify the major sources of P in wastewater influent at District WRPs, opportunities for source control by P harvesting from industry, and evaluation of several technologies for improved removal at WRPs, including biological P removal using P-accumulating bacteria or chemical precipitation with metal salts (Hey et al., 2005; Koch et al., 2015). However, these currently predominant technologies for P removal have important drawbacks, including instability in the former case, and the production of extra sludge with low P bioavailability in the latter case. Thus, there is continuing interest in developing new technologies that can remove additional P and avoid or improve on the key limitations of the current predominant approaches to P removal.

One promising approach to enhance nutrient removal at WRPs is to encourage the growth of photosynthetic algal biomass, which can continue to uptake nutrients after organic carbon is depleted. This occurs because photosynthetic growth can utilize inorganic carbon sources (CO_2, bicarbonate), which are generally available in excess at WRPs. In addition, if N becomes limiting, certain species of algae can fix atmospheric N and thus can balance the amount of the main macronutrients needed for biological growth (carbon, N and P). As a result, it is possible to remove nutrients to much lower levels with biological processes that include algal biomass. Other potential advantages of photosynthetic algal processes include the generation of oxygen, capture of CO_2, and the potential to use the resulting algal biomass for biofuels, animal feed, or biochemical – all of which are active areas of research and development. There are, however, some disadvantages associated with most of the previously proposed approaches to incorporating algal cultivation into wastewater treatment. In particular, most algal cultivation systems have relatively high land requirements because of the need to take in solar energy for photosynthesis. This is a particular problem for large urban WRPs because there is generally less nearby open land, and the value of that land is relatively high. Another important issue is that individual algal species are generally more sensitive to variations in the cultivation environment than the heterotrophic bacterial consortia used for typical aerobic wastewater treatment processes. This can be problematic for algal wastewater systems because they are subject to significant daily and seasonal variations in the influent wastewater quality as driven by changes in upstream activities, precipitation, and seasonal temperature fluctuations. A third critical issue for algal wastewater systems is scalability in order to process the extremely large water volumes associated with municipal wastewater treatment. Many algae cultivation approaches use HRTs in the range of 2 – 14 days, whereas the average HRT of most wastewater plants is less than one day. Thus, it is necessary to accelerate the rate water is passed through the algae cultivation system or use algae to treat concentrated wastewater side-streams in order to make the tank sizes and their associated costs reasonable.

This study proposed a novel system addressing the key shortcomings, as noted above, for integrating algae cultivation in wastewater treatment. Specifically, we will investigate the following tools for improving the performance of algae processes in wastewater applications:

(1) Submerged artificial lighting in open, flow-through tankage,
(2) Attached growth of algae on a plastic media, and
(3) Incorporation of regenerable adsorbents into the algae growing system.

This study investigated a range of relevant operating conditions (retention times, media type, packing density, gas feed rates, lighting intensity, etc.) and the primary metric for evaluating these alternatives will be P removal as a function of HRT, solids retention time, energy inputs, chemical inputs, gas inputs, and biomass productivity, all of which were used to determine estimated system costs.

BENCH-SCALE SYSTEM SETUP

In order to investigate and optimize the operational parameters, such as HRT and media-packing density, four 55-gallon cone bottom reactors were setup in the UCSD. As shown in Figure 1, a 4-foot tall submersible LED light tube was installed in the center of each reactor. Coarse bubble aeration was provided from the bottom of the reactor through a diffuser tube for mixing. Gas flow rotometers allow for adjusting the air-flow rate and air-mixing ratio if other gases, such as CO_2 or flue gas, are used. Influent water is continuously added into the reactor from the top, and the effluent exits the reactor through an elbow overflow port, where the outlet is 1 inch below the water surface to avoid floating algae clogging the outlet port. The port in the cone bottom can be used to harvest biomass or drain the system.

Anox^{TM} K5 disk-shaped media (ANOXKALDNES Inc.) was selected to provide a surface for biofilm development and retain biomass in the system (Figure 2). The K5 media is made of extruded high density polyethylene (HDPE) with the density of 0.95 kg/m^3. This webbed disk-shaped media with a diameter of 25 mm and a thickness of 5 mm provided 800 m^2/m^3 of protected surface area for biofilm growth. Ten gallons of unmodified K5 media was directly added into the LED-2 reactor to study the advantages of the plastic media over the suspended growth condition (LED-1). In order to facilitate biofilm formation and demonstrate the benefit of the adsorbents (zeolite and activated carbon), a sodium alginate-coating method was used to coat algae onto the media for the LED-3 reactor and coat both algae and adsorbents for the LED-4 reactor (Figure 2). Alginate is a natural polymeric material and widely used for encapsulation. It has a linear binary copolymer that can form a thermally stable and biocompatible hydrogel layer in the presence of calcium cations (Lee et al., 2013). The algal inoculant was harvested from the UCSD primary and secondary clarifiers to ensure compatibility with the wastewater matrix. Harvested algae was repeatedly rinsed until the washed water became clear. Washed algae was then blended with the alginate to create algae inoculant. Then, 300 g of wet algae inoculant was blended in five gallons of 4 percent sodium alginate solution. For the LED-4 reactor, an additional 450 g of zeolite and powdered activated carbon were mixed into the alginate solution. The K5 media were quickly dipped into the alginate solution while mixing and then bathed in 1.5 percent calcium chloride solution for at least one hour to form a solid alginate layer. Ten gallons of volume-equivalent, coated K5 media were separately prepared for LED-3 and LED-4 reactors (Figure 2).

The influent of this bench-scale system was drawn from the effluent of a denitrification tower and before a cloth filtration unit. As shown in Table 1, the influent water was relatively low in organic carbon but still had significant nutrient concentrations, which is favorable for algae cultivation. The major form of N was nitrate (10 - 20 mg-N/L) and the phosphate-P concentration ranged from 1-5 mg/L. Organic P was generally negligible (<0.1 mg/L).

The media-filling fraction is a critical factor to support biofilm growth and attain effective treatment efficiency. The maximum media-fill fraction of a standard moving bed biofilm reactor (MBBR) is usually below 66 percent (Neu, 2013). Azizi et al. (2013) reported the COD removal is almost constant after the filling fraction above 40 percent. However, past work on the optimal filling fraction is based on other wastewater treatment targets and has

FIGURE 1: BENCH-SCALE ALGAL BIOREACTOR SETUP AT THE URBANA-CHAMPAIGN SANITARY DISTRICT WASTEWATER PLANT

FIGURE 2: K5 MEDIA WITHOUT ANY COATING, ALGAE COATED K5 MEDIA FOR LED-3, AND MIXED ADSORBENT AND ALGAE COATED K5 MEDIA FOR LED-4

No Coating

Algae Coating

Mixed Adsorbent and Algae Coating

TABLE 1: INFLUENT WATER QUALITY OF THE BENCH-SCALE EXPERIMENTS

	Influent Water Quality	
	Average	Range
TSS (mg/L)	5.7	3 – 15
COD (mg/L)	18.4	5 – 30
CBOD[a]	7.2	2 - 20
TN (mg/L)	15	10 - 22
Ammonia (mg-N/L)	0.28	0.1 - 1
Nitrate (mg-N/L)	14.1	10 - 20
PO_4-P (mg-P/L)	2.1	1 - 5
Temp (°C)	20	16 - 22
pH	8.3	8.2 - 8.5

Notes: (a) Average of activated sludge and trickling filter effluent before nitrification towers

focused on bacterial biofilms instead of algal biofilms. Due to the need for distributing light to the media surface for algae growth, a higher degree of mixing and a lower filling fraction was expected to be beneficial. For the 55-gallon reactors, as shown in Figure 1, we went through a process of empirically testing different combinations of filling fraction and mixing energy to determine the amount of aeration required to maintain consistent media mixing. This work suggested that in order to maintain a good mixing pattern with a reasonable energy input, a filling fraction of 18 percent and an aeration rate of 10 cfm was a good combination for the bench-scale tests. In our bench-scale system, aeration is the major mixing mechanism, and it mainly provides vertical mixing. As a result, the optimal filling fraction should be revisited again in larger reactor testing with horizontal flow patterns.

Table 2 summarizes the key experimental conditions in the four bench-scale reactors over the ten months of testing. The first five trials sought to maximize treatment capacity by studying the effects of HRT on P removal as the key parameter for effluent water quality. In addition, these trials highlighted the effects of different algae/adsorbent coatings on effluent water quality, and the start-up time needed to reach steady performance. Each trial generally ran for two to three weeks. Trial 6 studied the effect of different biomass harvesting frequencies (i.e., solids retention time) on P removal. At the end of Trial 6, the control box for LED-1 was malfunctioning; therefore, we stopped taking samples from Reactor 1. This reactor did not have any media to support biofilm growth and thus always performed worse than the other configurations with media.

TABLE 2: SUMMARY OF OPERATING CONDITIONS USED IN BENCH-SCALE SYSTEM

Trial No.	Operating Condition	LED-1	LED-2	LED-3	LED-4
1	HRT: 24 hour	No-media+ algae	K5-media+ algae	K5-media+algae coating	K5 media+ adsorbent algae coating
2	HRT: 12 hour	No-media+ algae	K5-media+ algae	K5-media+algae coating	K5 media+ adsorbent algae coating
3	HRT: 6 hour	No-media+ algae	K5-media+ algae	K5-media+algae coating	K5 media+ adsorbent algae coating
4	HRT: 4 hour	No-media+ algae	K5-media+ algae	K5-media+algae coating	K5 media+ adsorbent algae coating
5	HRT: 6 hour	No-media+ algae	K5-media+ algae	K5-media+algae coating	K5 media+ adsorbent algae coating
6	HRT: 6 hour, SRT Test	No-media+ algae	K5-media+ algae	K5-media+algae coating	K5 media+ adsorbent algae coating
7	HRT: 6 hour, CO_2 Test		Mixed media, 0% CO_2	Mixed media, 4% CO_2	Mixed media 8% CO_2
8	HRT: 6 hour, CO_2 Test		Reduced light, 0%CO_2	Mixed media, 4% CO_2	Mixed media 8% CO_2
9	HRT: 6 hour, CO_2 Test		Change light duty cycle	Mixed media, 2% CO_2	Mixed media 6% CO_2
10	HRT: 6 hour, CO_2 Test		Change light duty cycle	Mixed media, 0.5% CO_2	Mixed media 1% CO_2
11	Concentrated side stream			HRT 50 day, 1% CO_2	HRT 25 day, 1% CO_2

At the start of Trial 7, we mixed all the media and evenly redistributed media back into reactors LED-2, 3, and 4 to study the effects of different CO_2 concentrations on reactor performance. In Trials 8, 9, and 10, we varied the light intensity and duty cycle experiments in reactor LED-2, while reactors LED-3 and 4 were used for additional testing of different CO_2 concentrations.

For Trial 11, reactors LED-3 and LED-4 were used to begin a study on the effect of HRT for treating concentrated wastewater side streams with much higher nutrient concentrations but much lower volumes. The LED tube originally in reactor 2 was moved to our 450 gallon large bench-scale reactor, which was used to study LED light spacing and horizontal mixing conditions.

BENCH-SCALE SYSTEM RESULTS

Effects of Adsorbent on Nutrient Removal at Different Hydraulic Retention Times

Typical HRTs of enhanced biological P removal systems reported in the literature range from 0.5 to 2 days with SRTs ranging between 8 to 25 days (USEPA, 2008a). This study sought to define the lowest HRT possible in an algal nutrient removal system while maintaining good nutrient removal (PO_4-P < 0.5 mg/L). During the startup phase, 300 grams of locally harvested algae was inoculated into LED-1 and LED-2 reactors, which resulted in an initial algae concentration of 50 mg/L. LED-1 and LED-2 were operated in batch mode for nine days to allow a biofilm to develop. Then, 10 gallons of algae coated and adsorbent-algae coated K5 media were added into LED-3 and LED-4, respectively, to start the HRT test. The HRT test started at 24 hours and then gradually stepped down to 12, 6, and 4 hours after steady-state performance was achieved, which generally took 10 to 20 days. The steady-state influent and effluent concentrations of PO_4-P and nitrate nitrogen (NO_3-N) associated with 24-, 12-, 6-, and 4-hour HRTs were measured, and both the average and standard deviation of these results are reported in Figures 3 and 4, respectively. The influent used for this experiment is the effluent from the denitrification tower, and natural P variations were observed due to weather and seasonal changes.

FIGURE 3: INFLUENT AND EFFLUENT ORTHOPHOSPHATE CONCENTRATIONS OF FOUR LED-LIGHTED REACTORS WITH DIFFERENT FIXED-FILM MEDIA CONFIGURATIONS OVER A RANGE OF HYDRAULIC RETENTION TIMES

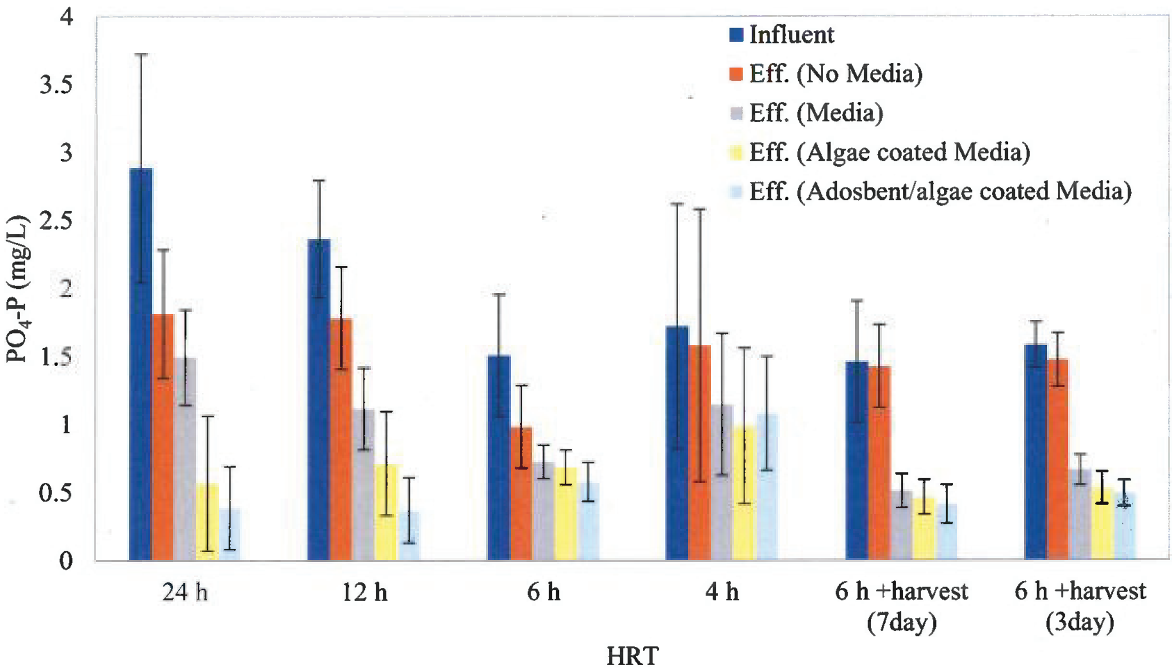
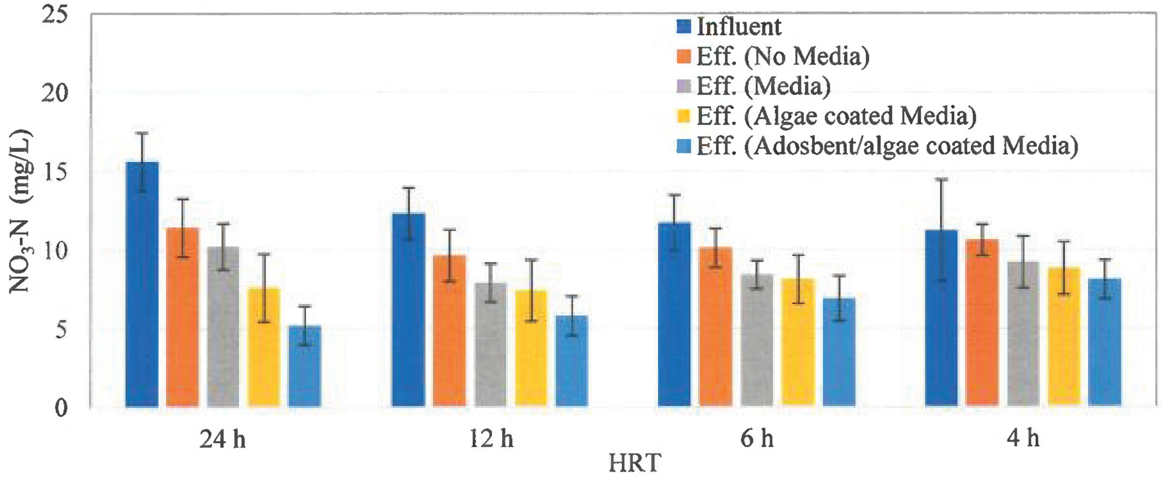


FIGURE 4: INFLUENT AND EFFLUENT NITRATE-NITROGEN CONCENTRATION OF FOUR LED-LIGHTED REACTORS WITH DIFFERENT FIXED-FILM MEDIA CONFIGURATIONS OVER A RANGE OF HYDRAULIC RETENTION TIMES



As shown in Figure 3, better P removal was achieved with both types of coated media (LED-3 and LED-4) than with no media (LED-1) or media without coating (LED-2). Over time, the performance of the media without any coatings improved relative to the coated media, but the uncoated media always performed worse. Although all reactors started with the same algae concentration, the coated media configurations had better performance because they retained more algae on the media and protected them from being washed out. In addition, the adsorbent coated media (LED-4) showed the best P removal. This result agrees with our previous studies on algal wastewater treatment systems, which showed that integrating adsorbents into the system can enhance the growth of biofilm and improve treatment performance. Our hypothesis is that the adsorbents like the zeolite used in this study can accumulate nutrients on its surface by physico-chemical adsorption, hence creating a local nutrient rich zone that encourages biofilm development and does not allow the nutrients to escape the treatment system. In addition, the adsorbents are thought to provide more surface area and a more favorable surface for the biofilm to colonize. Activated carbon adsorbents in particular are well known for creating an advantageous growth environment for microorganisms. Thus, more biomass was retained and nutrient removal was increased with the adsorbent coated media.

The difference between algae-coated media and uncoated media reduced significantly after six weeks of operation, which suggests that the amount of biofilm colonized on the media had essentially caught up to the amount on the initially coated media. This result suggested that alginate-coated media could save at least six weeks of startup time. In addition, the alginate-coated media is expected to be helpful for reducing recovery time if there were a reactor upset. Three-day and seven-day harvesting frequency were tested when the system was operated at six-hour HRT. These results showed that the effluent water quality was worse when the harvesting frequency was adjusted to once every three days, which indicated the system was being over harvested. Therefore, the final harvesting frequency was returned to once every seven days. Figure 3 shows that six-hour HRT and harvesting once every seven days had the best effluent quality, which was 0.51 mg/L, 0.46 mg/L and 0.41 mg/L for PO_4-P in the reactors with media, algae-coated media, and adsorbent/algae coated media, respectively.

Similar trends were also observed in NO_3-N removal, which was monitored because it is the major nitrogen form in the influent. As shown in Figure 4, the system with adsorbent and algae coated K5 media (LED-4) had the lowest nitrate concentration in effluent. Thus, this result also confirmed a benefit of implementing adsorbents into the system. Comparing Figures 3 and 4, it is apparent that the percent removal of N was lower than for P. Thus, there is sufficient N available in the system to support biological removal of P.

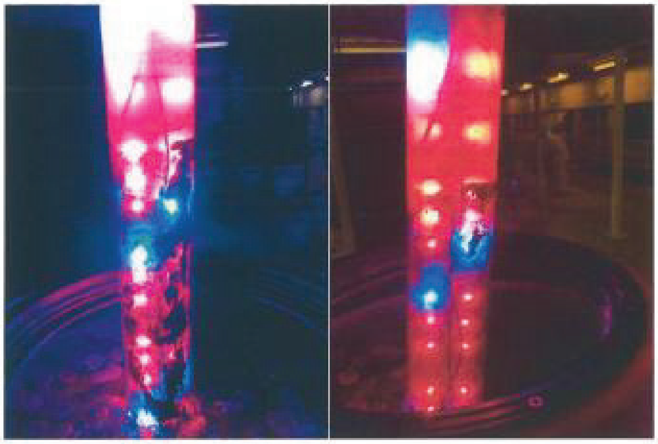
Among the four different HRT conditions tested (24, 12, 6, 4 hour), 4-hour HRT had the worst treatment performance (effluent PO_4-P > 1 mg/L). It is likely that the growth rate of algae did not keep up with the water flow rate. Iwai and Kitao (1994) reported the doubling time of wastewater-grown algae is between 7 to 25 hours. Since the P-removal mechanism for algae mainly relies on biological assimilation, when flow rate overwhelms the algae doubling time, washout of any suspended biomass will occur, which would lead to reduced nutrient removal efficiency. Six-hour HRT was the most optimal flow rate among the four conditions tested in balancing between treatment capacity and effluent quality. A 12-hour HRT was able to achieve more nutrient removal for most of the media configurations, but the efficiency of nutrient removal per tank volume would be lower because the process would be twice as large as the 6-hour HRT. Note that a process designed for 6-hour HRT at peak flows would usually operate at a higher HRT and achieve better nutrient removal because the average plant flow is usually significantly lower than peak flow.

Biomass harvesting is the major mechanism to ultimately remove P that is temporarily stored in the biomass from a biological assimilation system. It needs to be carefully managed because either excessive removal or deficient removal can both negatively impact system performance. In this study, vigorous mixing by aeration (40 cfm for 30 minutes) was used to scour biomass off the media surface and LED tube. As shown in Figure 5, after 30 minutes of air sparging, most of the biofilm was removed from the LED tube. Then the aeration was shut off to allow sloughed biomass to settle and be drained out of the bottom harvesting port.

Effects of Carbon Dioxide Addition on Effluent Quality and Biomass Productivity

Algae are similar to any other photosynthetic organisms that capture energy from light and fix CO_2 through the Calvin-Benson cycle during photosynthesis, which produce glucose and other biomass intermediates. However, deficient CO_2 supply can slow down the algae growth rate, while excess CO_2 can cause the pH to drop to a level inhibitory to algal growth. Many researchers have studied the optimal CO_2 concentration on algae productivity. For instance, de Morais and Costa (2007) studied the biomass productivity of *Spirulina* and *Scenedesmus* cultures with various CO_2 concentrations up to 18 percent (v/v). The results showed both strains performed best under 6 percent (v/v) CO_2 concentration. Kishimoto et al. (1994) reported an algae strain *Dunaliella* sp. achieved the highest productivity with three percent CO_2 additions. These cases highlight that different species grown under different cultivation conditions had different optimal CO_2 concentrations. The goal of this test was to find the optimal CO_2

FIGURE 5: BIOFILM ON LED TUBE BEFORE AND AFTER 30 MINUTES OF AIR SPARGING



concentration for the mixed cultures grown with the LED-enhanced, fixed-film system used in this study. Pure CO_2 from a cylinder was used and blended with ambient air used for the aeration introduced at the bottom diffuser tube for mixing. The effects of various CO_2 concentrations on biomass growth are shown in Figure 6.

Seven different CO_2 concentration conditions were tested (0 percent, 0.5 percent, 1 percent, 2 percent, 4 percent, 6 percent and 8 percent). Zero percent CO_2 concentration was done in LED 2 and the rest were done in LED 3 and LED 4. The order of the tests is shown in Table 2. The results suggested 1 percent and 2 percent CO_2 addition provided the best PO_4-P removal. Similar results can be observed in Figure 7, which shows the harvested biomass from the reactor with different levels of CO_2 addition. The amount of harvested biomass peaked at 1 percent CO_2 concentration and then slowly decreased. This result confirmed that the excessive CO_2 concentrations could reduce the biomass production. However, all the tested CO_2 concentrations from 0.5 percent to 8 percent resulted in improved biomass production and PO_4-P removal in comparison to the baseline condition of using ambient air without adding CO_2.

Figure 8 shows the effect of CO_2 addition on the algae biofilm development. The system with CO_2 addition showed a generally darker green color and had thicker biofilm colonized on the media, which also highlighted the benefits of increasing the CO_2 concentration in the system.

Light Intensity, Duty Cycle, and Flashing Tests

Light energy added to the system is not only a critical parameter for supporting photosynthetic organism growth, but it also is the major energy consumer for the whole system. Therefore, it is important to optimize lighting conditions to provide sufficient light for photosynthesis, while minimizing energy consumption. Several characteristics of the lighting can have impacts on the photosynthetic efficiency, including light intensity, wavelength, flash frequency, and duty cycle. Blue and red LEDs were used in this study because they are the most effective wavelengths for photosynthesis (Fu et al., 2012). This test aimed to test different light conditions to reduce the light energy inputs while maintaining good nutrient removal.

FIGURE 6: EFFLUENT ORTHOPHOSPHATE CONCENTRATIONS WITH DIFFERENT CARBON DIOXIDE CONCENTRATIONS IN THE GAS FEED

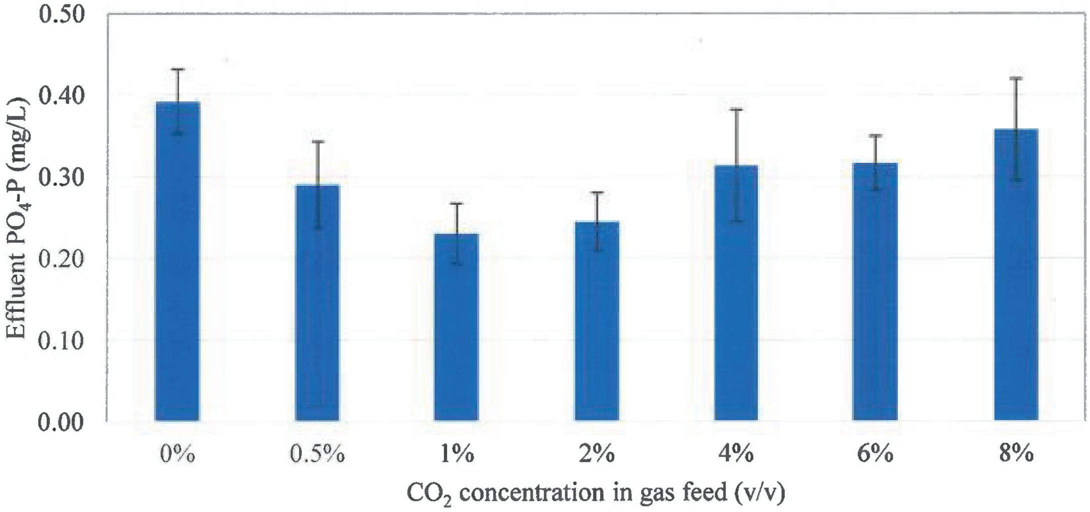


FIGURE 7: HARVESTED BIOMASS AT DIFFERENT CARBON DIOXIDE CONCENTRATIONS IN THE GAS FEED

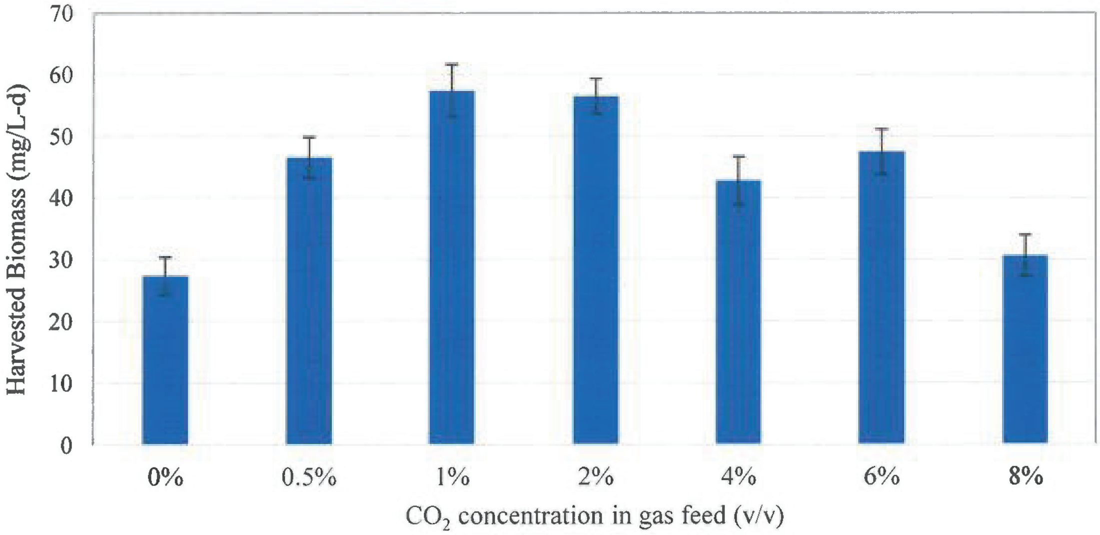
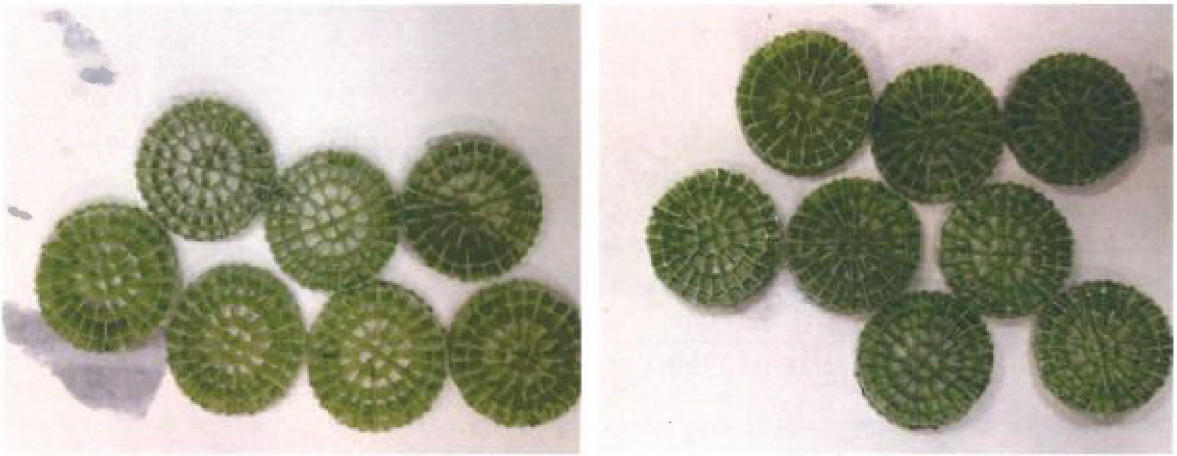


FIGURE 8: ALGAE COLONIZATION OF MEDIA WITH 0 PERCENT CARBON DIOXIDE AND 4 PERCENT CARBON DIOXIDE ADDED



0% CO_2

4% CO_2

Three main light conditions were examined, namely: (1) Constant full-strength light (360W); (2) 72 W of light energy with a light:dark duty cycle of 1:1 and a 10 ms flashing frequency; and (3) 48 W of light energy with a light:dark duty cycle 1:2 with a 10 ms flashing frequency. The adjusted light intensity was 40 percent of the full-strength light condition and was determined by gradually lowering the light intensity until no light was visible on the outside wall of the reactor.

Figures 9 and 10 show the influent and effluent PO_4-P and NO_3-N concentrations, respectively, for the three different lighting conditions, one of which was replicated. The results showed that reducing light energy from 360 W to 72 W had no significant impact on the nutrient removal, but further reductions to 48 W by changing to a light/dark cycle of 1:2 (33 percent duty cycle) led to increasing effluent nutrient levels. The photon flux of the two LED colors can be calculated based on the Planck-Einstein relation. The calculation showed the photon flux on the surface of the LED tube was 1800 $\mu mol/m^2$-s during the full-strength lighting. In the literature, algae photosynthetic efficiency generally peaks between 300 to 500 $\mu mol/m^2$-s (Formighieri, 2015). Therefore, the light intensity at full strength is clearly exceeding the light-saturation point and wasted a significant amount of energy. For the light adjusted to 40 percent of full strength, the photon flux is 720 $\mu mol/m^2$-s on the surface of the LED tube, which is generally higher than the light saturation point. However, a slightly higher intensity also allows a greater light penetration distance, which ended up transferring light energy more efficiently. In addition, flashing the lights provides a dark cycle that allows algae to re-oxidize the electron transporters of the photosynthetic apparatus (Sforza et al., 2012). Consequently, it is not surprising that flashing the lights at the adjusted intensity resulted in higher photosynthetic efficiency. The adjusted intensity + 33 percent duty cycle condition showed that additional dark cycle time would reduce nutrient removal efficiency.

FIGURE 9: INFLUENT AND EFFLUENT ORTHOPHOSPHATE CONCENTRATION DURING LIGHT ENERGY REDUCTION TESTS

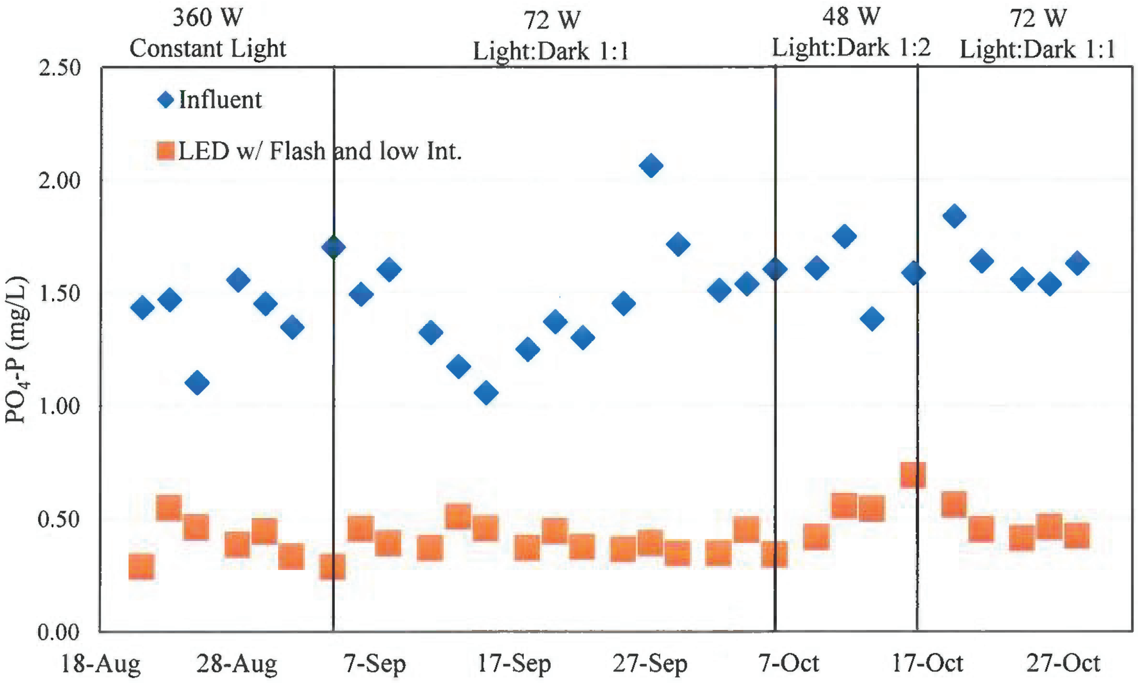


FIGURE 10: INFLUENT AND EFFLUENT NITRATE-NITROGEN CONCENTRATION DURING LIGHT ENERGY REDUCTION TESTS

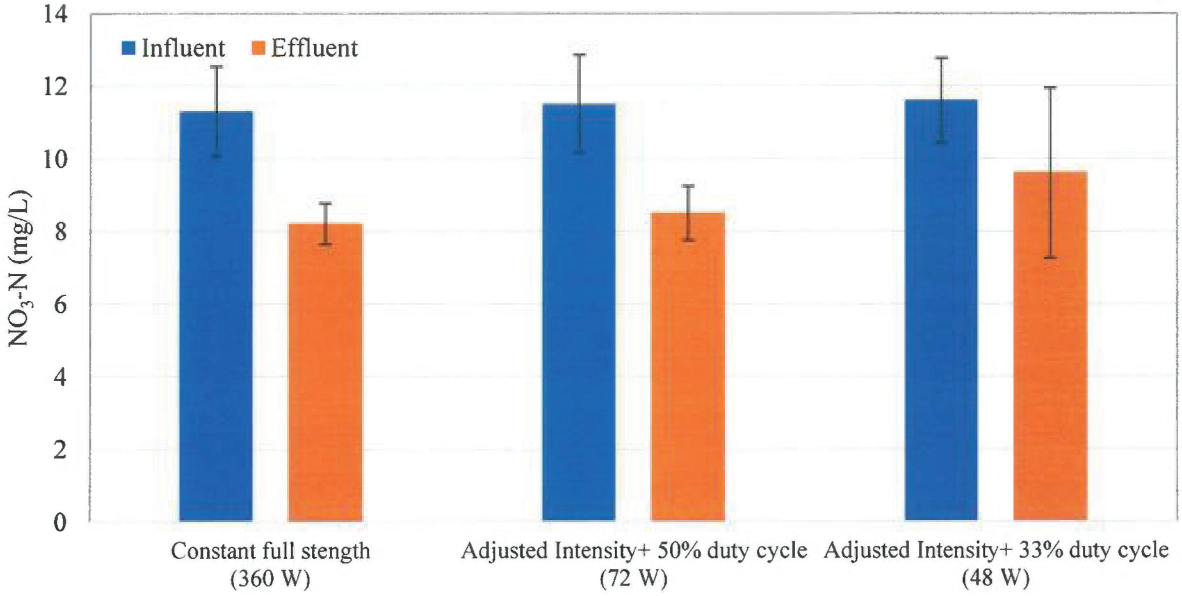


Table 3 shows the elemental characteristics of the harvested biomass. The harvested biomass P content is higher than general algae strains. Ashok et al. (2014) studied the nutrient removal using algal-bacterial mixed culture, and also found that the amount of N and P uptake were far in excess of the stoichiometric N and P requirement for the growth of biomass. This can be attributed to the luxury uptake by both algal and bacterial biomass, which can store excess nutrients for future metabolic activities. In addition, our system encourages fixed-film biomass growth and the associated production of extracellular polymers (EPS). Cloete and Osthuizen (2001) studied the microbial P removal mechanism and the X-ray microanalysis showed that EPS can account for up to 30 percent of the P removal in these systems.

Biomass Sedimentation Test

Total suspended solids (TSS) is a key permitting criterion for wastewater plant discharges. During the HRT tests, we noticed the effluent TSS from the algae cultivation tanks was increased, which is possibly due to the growth of suspended algae and biofilm sloughed off the media by mixing. Therefore, a clarifier or filter will be needed to reduce TSS in the effluent. This testing aimed to study the settle ability of the solids in the effluent and then use these data to determine sizing criteria for a downstream clarifier.

An initial sedimentation test was conducted in 20-gallon buckets. Water was drained from the side port of each reactor and then left to sit unstirred. A sample was taken from 1 inch below the water surface at 0, 10, 30, 60, and 120 min. The TSS results over time are shown in Figure 11. The zero minute data represents the effluent as it directly flowed out of the reactors, which were 31.2, 27.4 and 28.2 mg/L for reactors with media, algae-coated media, and adsorbent/algae-coated media, respectively. Considering the fact that the TSS of the influent ranged between 3-15 mg/L, the results highlight that the algae treatment system introduced extra particles to the effluent. Even though the system focuses on enhancing fixed-film algae growth on the media, there is suspended biomass from free-floating algae reproduction and biofilm that sloughs off the media, which eventually increased the TSS in the effluent.

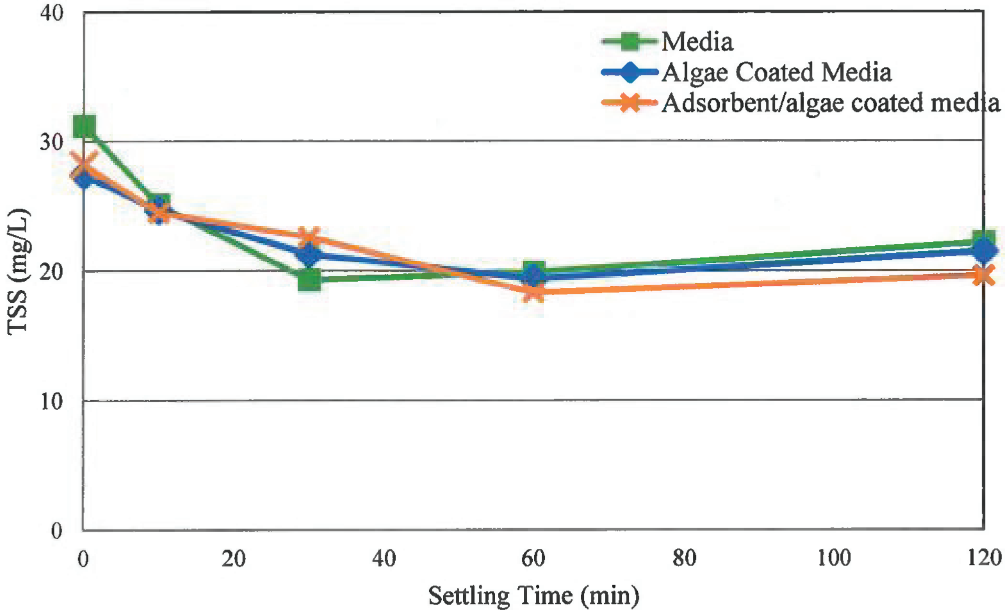
TABLE 3: ELEMENTAL ANALYSIS AND HIGHER HEATING VALUE OF HARVESTED BIOMASS

Biomass Characteristics	
C (%)	46.3 ± 3.2
H (%)	6.6 ± 1.4
N (%)	6.7 ± 1.2
P (%)	5.1 ± 0.4
*O (%)	35.2
**HHV (MJ/kg)	18.9

*Oxygen content was calculated based on subtraction of other elemental contents from 100 percent.

**Higher heating value was calculated based on the Dulong equation (Chen et al., 2014).

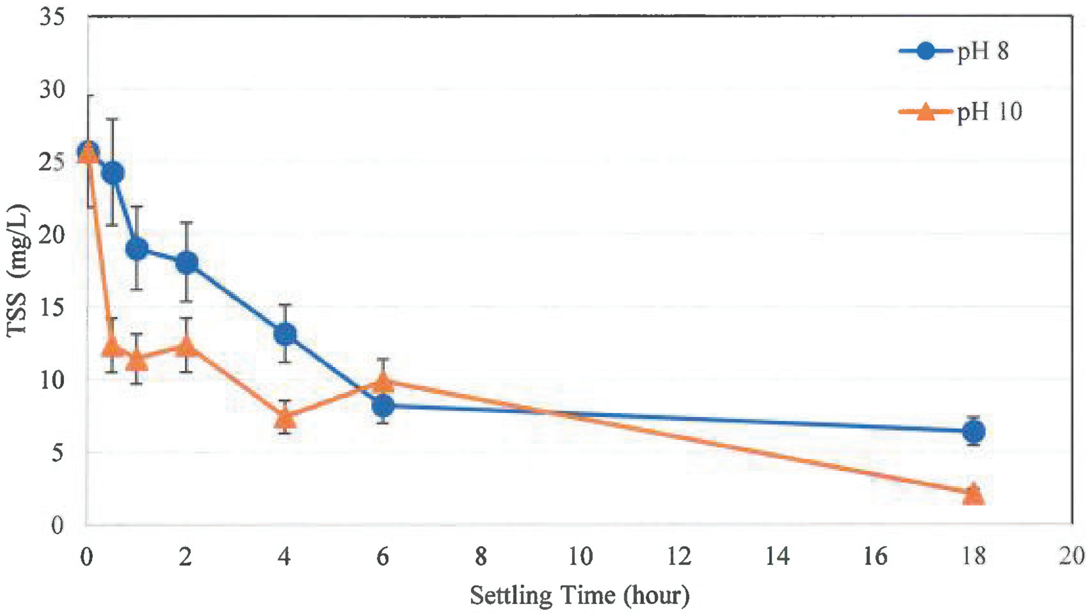
FIGURE 11: TOTAL SUSPENDED SOLIDS OF DIFFERENT REACTORS OVER A RANGE OF SETTLING TIMES



Based on the data in Figure 11, TSS steadily decreased for 40 - 60 minutes. After two hours of settling, the TSS in the effluent of reactors with media, algae coated media, and adsorbent/algae coated media were 22.2, 21.5 and 19.6 mg/L, respectively. This result indicates that the biomass in the effluent had relatively low settle ability, which is common for suspended algae cultivation systems but rarely found in the fixed-film system. Filtration or flocculation of all or part of the effluent could be integrated into the system to lower effluent TSS concentrations and meet discharge regulations.

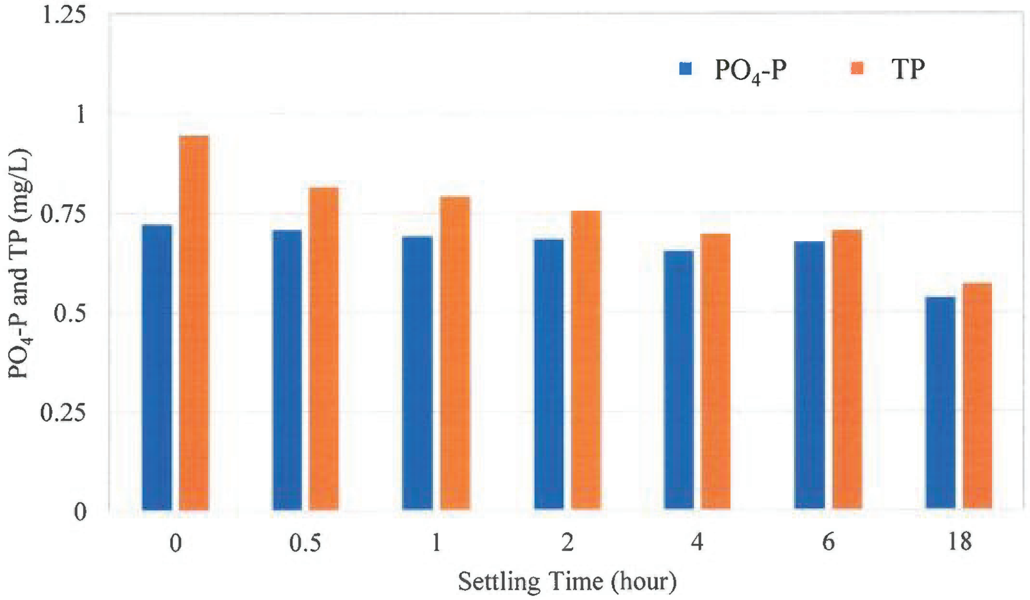
A second sedimentation test was conducted to investigate the effects of pH-induced flocculation of algae, which can be induced naturally or by adding a base. Sukenik and Shelef (1984) found that natural flocculation of *Scenedesmus dimorphus* was obtained simply by ceasing pond agitation and cutting off the CO_2 supply in an outdoor culture. In a recent study, it was shown that the diatom *Phaeodactylum tricornutum* could naturally increase the pH of a culture to higher than its pH of flocculation (Spilling et al., 2011). Different behavior was observed with the green microalga, *Scenedesmus obliquus*: the pH of the culture could increase but not enough to achieve flocculation, for which the addition of a base was necessary (Lavoie and de la Noue, 1987; Spilling et al., 2011). In this test, the pH of the effluent was chemically adjusted from 8 to 10 by adding a sodium hydroxide solution. The settling time was also extended to 18 hours to fully explore the TSS reduction over time. The results are shown as Figure 12, which showed that the effluent TSS decreased faster for the pH-adjusted sample. Fifty percent of TSS in pH-adjusted effluent was settled within the first 30 minutes, while the sample without a pH adjustment took four hours. This test clearly showed the benefit of pH-induced flocculation on sedimentation rates. However, the economics of using chemicals for pH adjustment need to be further evaluated and are discussed later in this report.

FIGURE 12: pH-INDUCED FLOCCULATION SEDIMENTATION TEST ON LED-4 EFFLUENT



The relationship between orthophosphate (PO_4-P) and TP in the effluent was studied during the sedimentation test. Both PO_4-P and TP were measured using the Hach procedure and Environmental Protection Agency P measurement guidelines 365.1 and 365.2 (USEPA, 1994). According to the procedure, a TP measurement can measure both dissolved and particulate P while the orthophosphate method measures mostly dissolved PO_4-P and parts of particulate PO_4-P due to the acidity of the reagent. Therefore, both measurements decreased as the TSS in effluent decreases. The difference between PO_4-P and TP measurements at 0 hour represented the sum of condensed phosphate, organic P, and particulate PO_4-P that was not measured by the PO_4-P measurement. After 18 hours of sedimentation, the difference between the PO_4-P and TP measurement is significantly smaller (Figure 13). This result indicated that most of the P species in the effluent after sedimentation are dissolved PO_4-P. Nevertheless, by comparing the difference of TSS removal and TP reduction over 18 hours, sediment biomass P content can be calculated, which was 2.1 percent. While Table 3 shows the P content of the reactor harvested biomass is 5.1 percent, it is believed that the major composition of the suspended biomass and the harvested biomass are different. Approximately 2 - 3 percent P content is commonly found in effluent particulates (Strom, 2006). Our hypothesis is that the majority of reactor harvested biomass is sloughed biofilms that have developed algal-bacterial consortia that have higher P content. Cloete and Osthuizen (2001) also reported EPS from biofilm may act as a P reservoir and enhance microbial P uptake by 30 percent. The P luxury uptake from algal-bacterial consortia need to be further studied.

FIGURE 13: ORTHOPHOSPHATE AND TOTAL PHOSPHORUS CONCENTRATION CHANGES OVER TIME IN LED-4 EFFLUENT



Side Stream Test

Phosphorus removal in concentrated side streams was also tested in this study. As shown previously in Table 1, Reactors 3 and 4 were used to study nutrient removal from an anaerobic sludge dewatering centrate using the LED-enhanced, fixed-film algal nutrient removal system. The centrate was collected in a storage tank with a cone bottom and settled for at least six hours. Once the sedimented sludge was removed from the tank, centrate supernatant was fed into the LED reactor at designated rates. The water quality of the centrate supernatant is shown in Table 4. The reactive phosphate concentration in this centrate is about 150 times higher than the main stream nitrification effluent used previously in this study. The previous experiments showed that the main stream can be effectively treated at 6 hour HRT. Assuming the same P removal rate, centrate would require a 37.5 day HRT to be fully treated. In order to explore the effects of HRT on centrate P- removal efficiency, 25 and 50 day HRT were tested and compared.

The influent and effluent water quality results with a 25- and 50-day HRT are shown in Figures 14 - 16 (Note that the influent levels are plotted using a second y-axis on the right of these figures). Influent samples were taken at the beginning of each refilling event and are expected to remain fairly constant between refills. The result shows that influent water quality (sub y-axis) had great variation between the different collection events. This can be due to the different operational status of the centrifuge operations during different collection events. The lower values can be caused by stable operations, higher centrifuge spinning speeds, or lower centrifuge loading rates. The effluent PO_4-P concentration for both 25 and 50 days HRT were below 1 mg/L until the second batch of centrate was used. As shown in Figure 14, both the influent and effluent PO_4-P concentration of 25-day HRT increases dramatically right after the

TABLE 4: URBANA-CHAMPAIGN SANITARY DISTRICT ANAEROBIC SLUDGE CENTRATE SUPERNATANT WATER QUALITY

Parameters	Average
TSS (mg/L)	118.3 ± 54.9
COD (mg/L)	372 ± 62.4
Ammonia (mg-N/L)	942.1 ± 192.6
Nitrate (mg-N/L)	19.8 ± 3.2
PO_4-P (mg/L)	303 ± 74.2
pH	8.3

FIGURE 14: INFLUENT AND EFFLUENT ORTHOPHOSPHATE CONCENTRATION IN CENTRATE TEST

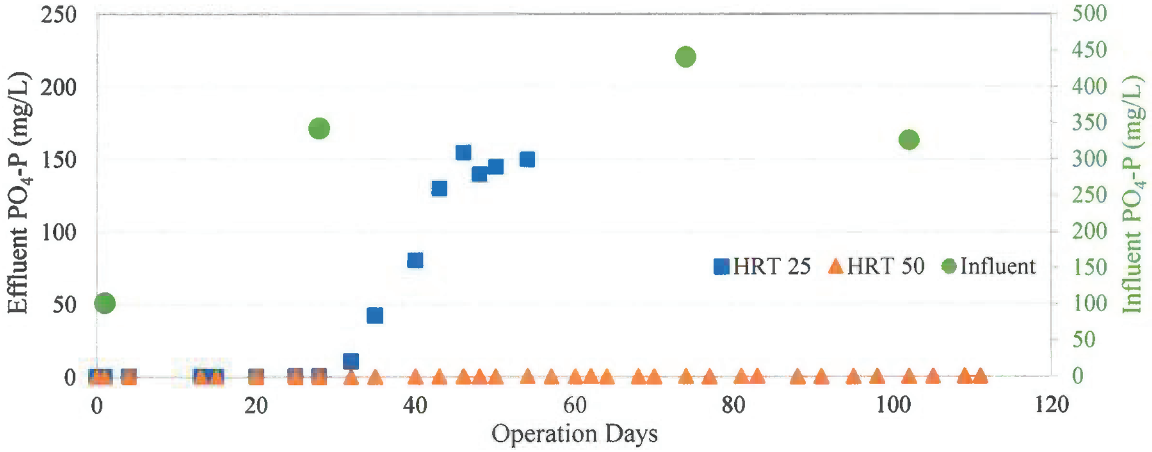


FIGURE 15: INFLUENT AND EFFLUENT AMMONIA-NITROGEN CONCENTRATION IN CENTRATE TEST

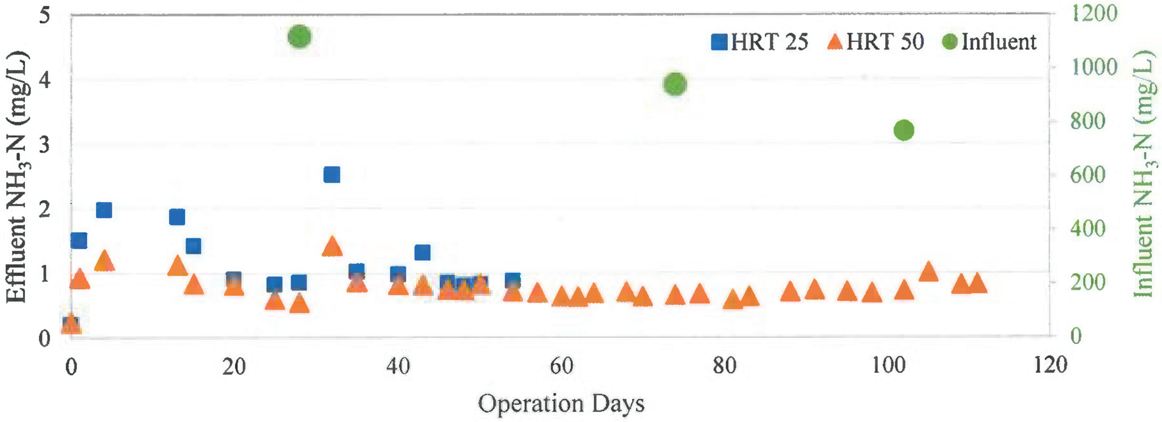
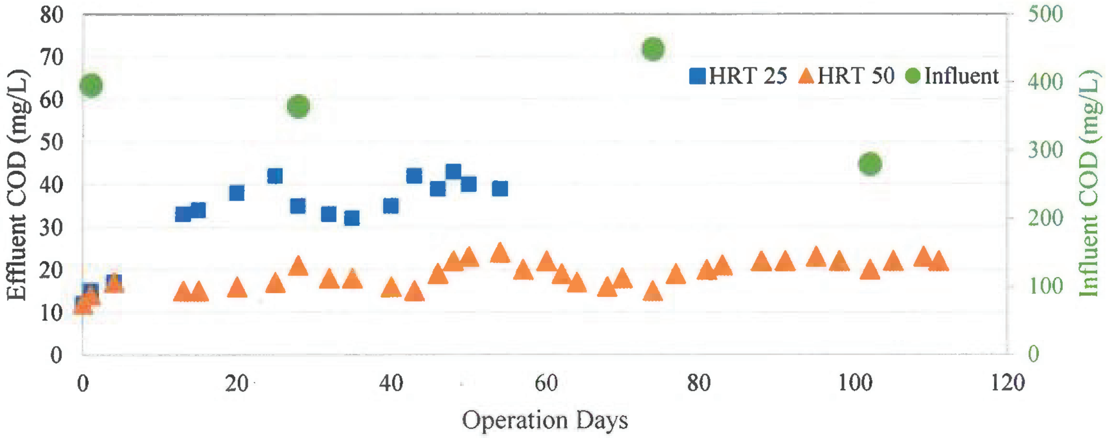


FIGURE 16: INFLUENT AND EFFLUENT CHEMICAL OXYGEN DEMAND CONCENTRATION IN CENTRATE TEST



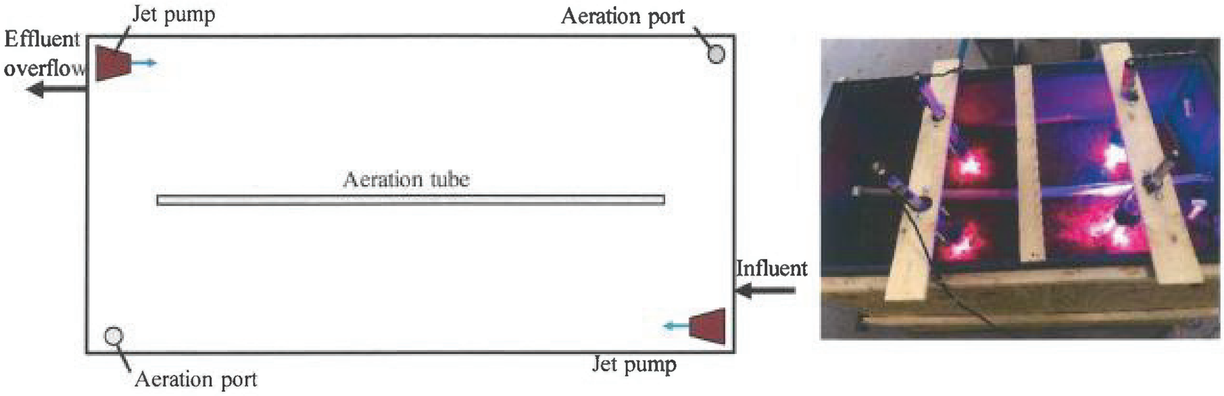
second batch of centrate was added. This new batch of centrate essentially created a shock loading in the 25-day HRT reactor, causing the algal biofilm to be inhibited, and the green biofilm color faded rapidly. Interestingly, the removal of NH_3-N recovered within seven days after a second batch of centrate was used. This is an indication that algae may have been overrun by nitrifying bacteria when the system lost the ability to remove P. For the 50-day HRT test, the variation of influent water quality did not affect the P removal efficiency. In this case, the algae culture was able to handle the shock loading. However, even for side stream treatment, a 50-day HRT would most likely be a larger process footprint than the mainstream system. Longer HRTs also favor the growth of suspended algae, which is generally more difficult to harvest. For these reasons, side-stream applications of the algae system used in this study are considered less desirable.

LARGE BENCH-SCALE REACTOR

Large Bench-Scale System Setup

A single large bench-scale system (450 gal) was constructed for this study to further investigate parameters for a pilot-scale system that were not able to be fully tested in the small (55 gal) bench-scale reactors, such as media flow pattern, light spacing, and harvesting method, etc. The large bench-scale system, as shown in Figure 17, was constructed in a rectangular polyethylene tank (74"L x 38"W x 50"H), which was used to better simulate a much larger rectangular tank pilot-scale system proposed for further upscale testing at the District.

FIGURE 17: LARGE BENCH-SCALE SYSTEM SETUP



A wooden frame was built to prevent the polyethylene tank from deforming, and 20 gallons of colonized media were mixed with 80 gallons of fresh plastic media that was added into the tank for startup. Jet pumps were installed at the corner close to influent and effluent ports. Each pump capacity was 3000 LPH, which was sufficient to create a circular flow pattern in the horizontal direction with a desirable level of mixing. In order to provide a vertical component in the overall mixing flow pattern, an aeration tube was installed along the midline in the bottom of the tank. Then, the vertical water circulation pattern was investigated through underwater filming. As shown on the left side of Figure 18, insufficient vertical flow could be observed by a lack of the floating plastic media near the bottom of the tank, which would lead to inefficient use of the space and light energy in this region. The aeration flow rate was gradually increased until the plastic media consistently circulated through the bottom area of the tank. A total air-flow rate of 50 cfm was found empirically to provide sufficient vertical mixing in the large rectangular bench-scale system, which is shown in the picture on the right of Figure 18. Biomass was harvested by a wet vacuum pump after allowing the mixed algal biomass to settle for 30 minutes without any aeration. The energy used for the aeration and jet pump was recorded and compared with the light-energy consumption. Approximately 85 percent of the total system energy would be used for lighting when four LED light units were used. The lighting energy percentage increased to approximately 90 percent when six LED lights were used in the same tank.

FIGURE 18: UNDERWATER PHOTOS AT THE TANK BOTTOM FOR ASSESSING VERTICAL MEDIA FLOW PATTERNS

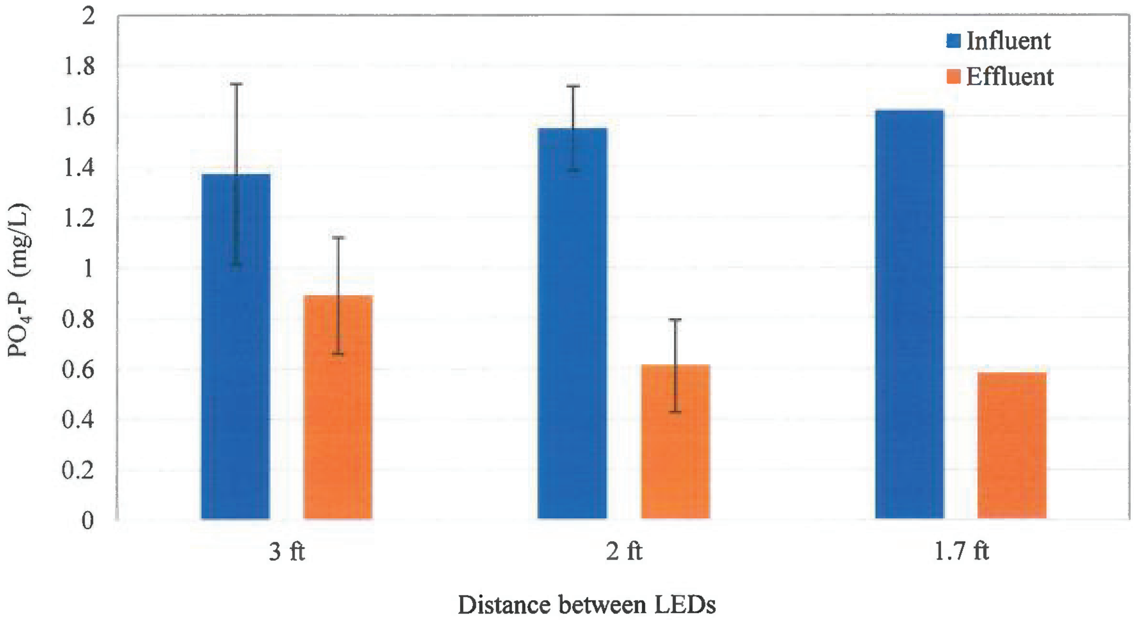

Deficient Vertical Flow Sufficient Vertical Flow

Light Spacing Test

As will be discussed later in this report, the largest single cost for equipment in the proposed algae treatment system is the LED light units. Therefore, it is important to minimize the number of light units used while maintaining a desirable removal efficiency. However, decreasing the light spacing has the potential to provide more treatment in a smaller space and thus lead to savings in tank costs. In order to study the effect of distance between LEDs on the P removal, two, four, and five LED units were installed in the reactor at different times, which resulted in the distance between LED units being varied from 3 ft to 2 ft to 1.7 ft, respectively. Full-strength light intensity was used during the initial light-spacing test.

As shown in Figure 19, the effluent PO_4-P concentrations are 0.89 mg/L, 0.61 mg/L and 0.58 mg/L for the distances between LEDs of 3 ft, 2 ft and 1.7 ft, respectively. The result showed that the removal efficiency could in fact be increased as the distance between lights decreased. However, even when the light distance was reduced to 1.7 ft, which is less than the diameter of the small bench-scale reactor, the nutrient removal was still not quite as good as the small bench-scale reactors. This result could be caused by less favorable mixing patterns or dead spots in the flow pattern, which reduces the average photosynthetic efficiency. Alternatively, the biofilm colonization of the plastic media in the larger reactor may not have fully reached steady-state during the time allotted for this testing. Future research on upscaling the pilot system should focus on improving the media mixing and water-flow patterns, aiming to reproduce or exceed the performance of the small bench-scale reactors.

FIGURE 19: INFLUENT AND EFFLUENT ORTHOPHOSPHATE CONCENTRATION FOR LED UNITS DISTANCE



TECHNO-ECONOMIC ANALYSIS

Techno-Economic Analysis Approach

A preliminary TEA was performed to document the conceptual design and operating parameters for an LED-enhanced, fixed-film algal nutrient removal system to be implemented at an existing wastewater facility with 100 MGD capacity. The key design parameters for the Baseline Design Condition, such as nutrient removal efficiency, HRT, biomass productivity, and LED light intensity, were adopted from the laboratory experiments described earlier. In addition, the TEA evaluated an Advanced Design Condition, which considered several potential system enhancements that are considered to be readily achievable in the near term and are expected to have a major impact on economic performance.

General Cost Estimation Basis

According to the cost estimation guidelines provided by the American Association of Cost Engineers, this study is considered as a Class 4 Estimate, which is the feasibility or pre-design estimate. This class is prepared using cost curves and scaling factors for major processes. Cost accuracy ranges from -30 percent to +50 percent. Capital costs were estimated from a variety of resources, including vendor quotes, USEPA cost estimation reports, and scientific literature. All costs included in this report are on a 2018 constant-dollar basis. All capital-cost information was adjusted to the 2018 equivalent cost basis using RSMeans Construction Cost Indices (2018):

$$Cost\ in\ 2018\ (\$) = equipment\ cost\ in\ quote\ year\ \times \frac{2018\ index = 215.8}{quote\ year\ \ index}$$

In addition, the scale of capital-cost items was adjusted to match the target 100 MGD capacity using typical scaling terms in the following equation:

$$Scaled\ equipment\ cost = cost\ at\ original\ scale\ \times (\frac{scale\ up\ capacity}{original\ capacity})^n$$

where n is the scale factor, typically 0.6 to 0.7.

Once the equipment is scaled and adjusted to the 2018 cost year, markup factors were applied to calculate the total capital cost. The total direct cost is the sum of all the installed equipment costs plus the estimated costs for additional piping (10 percent), site work (5 percent), and site electrical and controls (20 percent). Indirect costs were estimated at 35 percent of the total installed costs. The sum of the direct and indirect costs was the total capital cost.

Since the proposed system is considered to be an expansion of an existing WWTP, only the additional equipment/process units were included in the total capital cost estimation. Since the equipment could be allocated to the removal of both N and P nutrients, the capital cost of the expansion system was allocated with an even split for each nutrient. Thus, the capital cost allocation of the LED-enhanced, fixed-film algal nutrient-removal system for P removal was half of the total capital cost of the expansion system. The annualized capital costs were then calculated assuming a 4 percent interest rate and a 20-year amortization period. Note that land costs were not included in this evaluation.

The system's operating and maintenance (O&M) costs considered four categories: labor to operate the proposed expansion to the treatment system, reagent usage for the expansion system, maintenance for the expansion system, and whole plant energy usage. In order to line up the nutrient-removal cost for the proposed algae treatment system with other data reported in the literature (USEPA, 2008a; USEPA, 2008b; USEPA, 2015), the whole plant energy usage included energy usage for the expansion system and the power draw of the blowers, mixers, and pumps used for the secondary treatment because these processes would provide the major means of nutrient removal in the wastewater plant. When calculating the unit cost for TP removal, allocation of the whole plant energy usage was done as follows:

1. The energy usage of the expansion system was allocated to both N and P removal; the allocation of costs was evenly split.

2. For the secondary treatment system energy costs, the allocation was based on the typical oxygen demand by PAOs, nitrifiers, and heterotrophic organisms. Specifically, the allocation was 10 percent for P removal, 50 percent for nitrogen removal and 40 percent for BOD removal.

Subsequently, the operating and maintenance cost per unit of nutrient removal was then calculated using the following equation:

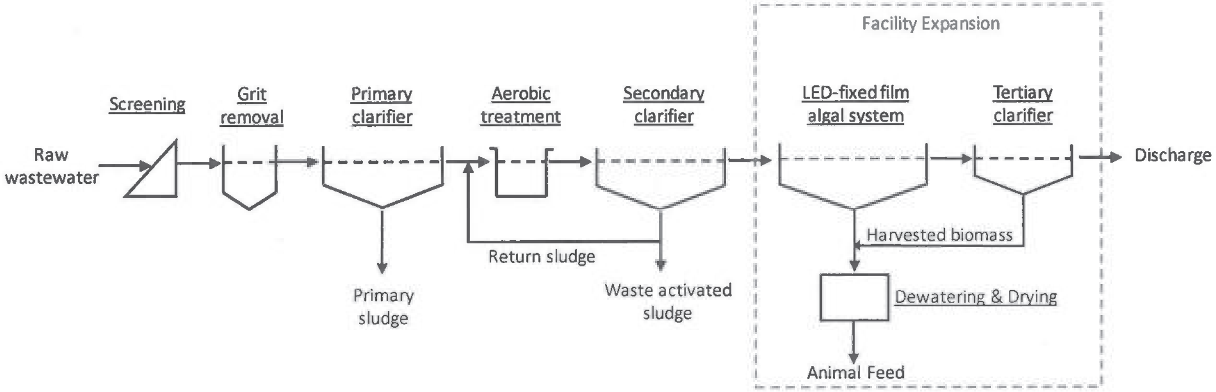
$$Nutrient\ Removal\ O\&M\ unit\ cost\ (\frac{\$}{lb}) = \frac{Expansion\ system\ (Labor, Chemical, Maintanence) + Whole\ plant\ (Energy\ usage) \times Allocation\ factor}{Whole\ plant\ nutrient\ removal}$$

Process Design and Cost Estimation

This section describes the basis of design and costing for a wastewater plant retrofitted with an LED-enhanced, fixed-film algal nutrient-removal system. The main purpose of the proposed system was to achieve a low level of TP discharge (less than 0.5 mg/L) by expanding existing facilities. The process model was formulated based on a 100 MGD conventional water reclamation facility (WRF).

Overall System Design Description. The LED-enhanced, fixed-film algal nutrient removal system is considered as an expansion of an existing wastewater facility. As shown in Figure 20, a typical WWTP includes preliminary treatment, primary treatment, and secondary treatment. Preliminary treatment consists of the screening of large debris and settling of grit, which is usually sent to a landfill. Primary treatment involves the physical settling of solids from the wastewater in a primary clarifier. Secondary treatment includes aerobic process means to remove biodegradable organics and total suspended solids. Thirty - 70 percent of N and 40 - 90 percent of P can also be removed in secondary treatment (Barnard, 1976; Bond and Rees, 1998). Subsequently, an LED-enhanced, fixed-film algal nutrient-removal system was added into the conventional treatment train as a tertiary treatment unit. In the lab study described earlier in this

FIGURE 20: WASTEWATER TREATMENT PLANT WITH LED-ENHANCED, FIXED-FILM ALGAL NUTRIENT REMOVAL SYSTEM EXPANSION PROCESS DIAGRAM



report, a tertiary clarifier was found to be necessary to maintain a low TSS in the discharge effluent. Algal biomass can be valuable if sold as animal feed. Therefore, a dewatering and drying unit for the algae was also included in the expansion system for biomass processing.

Table 5 shows the treatment performance presumed at different stages of the proposed system. The values used in this study are adopted from typical field-operation data obtained at the UCSD and from the laboratory experiments described earlier. The TSS in the algal treatment system increased due to the growth of free-floating, suspended algal biomass. The growth of suspended algae also caused incomplete TN and TP removal. Therefore, a tertiary clarifier or other TSS removal units were included to ensure the plant effluent meets the relevant discharge regulations.

TABLE 5: OVERALL SYSTEM TREATMENT PERFORMANCE AT DIFFERENT STAGES

	Raw Wastewater	Secondary Clarifier Effluent	LED Algae System Effluent	Tertiary Clarifier Effluent
TSS (mg/L)	200	15	25	>10
TN (mg/L)	30	15	12	>10
TP (mg/L)	6	2	1	>0.5

Table 6 shows the expected annual algal biomass productivity and the amount of nutrient removal for whole plant and expansion unit only. Similar to the system treatment performance, these values were estimated based on experimental results and then scaled for a 100 MGD plant. In order to compare the nutrient-removal costs with other biological nutrient-removal

TABLE 6: SYSTEM ANNUAL ALGAL BIOMASS PRODUCTION AND NUTRIENT REMOVAL PERFORMANCE

Item	Value	Unit
Algal biomass production	4,200	tons/yr
Whole plant - Nitrogen removal	2,800	tons/yr
Expansion unit - Nitrogen removal	416	tons/yr
Whole plant - P removal	763	tons/yr
Expansion unit - P removal	208	tons/yr

technologies that can be retrofitted into a WRF, whole plant nutrient removals were used to compute the unit cost of nutrient removal. The energy usage of aerobic treatment was included in the O&M costs because biological secondary treatment is a major means of nutrient removal for WRFs. Allocation factors were applied to apportion part of the energy usage for the aerobic treatment to the removal of N and P nutrients as described in the previous section.

LED-Enhanced, Fixed-Film Algal Nutrient-Removal System Cost Estimation. One of the major goals for this study was to evaluate the techno-economic feasibility of an LED-enhanced, fixed-film algal nutrient-removal system. The cost estimate for a Baseline Design Condition was formulated based on our bench-scale system operational experience. This experience showed that lighting energy accounts for 80 - 90 percent of the total algal system energy consumption. Therefore, we also want to consider an Advanced Design Condition that includes several near-term strategies for lowering the energy consumption in LED-lighted algae systems.

Table 7 shows the key parameters used for calculation of the energy consumption for nutrient removal with separate columns showing the results for the current Baseline System and a future Advanced System with improvements we have identified during this study. The current LED efficiency is the efficiency of converting electricity to light energy, also called wall-plug efficiency. Based on the current system LED specifications, the average wall-plug efficiency for the LED tube is 45 percent, which was used in the Baseline Design Condition. The CREE is one of the leading LED manufactures and has recently released a new type of LED (XP-G3) that is commercially available with 81 percent wall-plug efficiency, which was used in the Advanced Design Condition. The Baseline photosynthetic efficiency was calculated based on the light energy provided in the current system divided by the heating value of harvested biomass. In the Advanced system, the addition of CO_2 can further improve the photosynthetic efficiency as shown in the results presented earlier. The P and N content of the biomass were measured using the ICP-MS system and a CHN analyzer, which were used to calculate the heating value of the biomass.

TABLE 7: NUTRIENT REMOVAL ENERGY CONSUMPTION CALCULATION

	Current	Advanced
LED Efficiency (%)	45	80
Photosynthetic Efficiency (%)	16	23
Biomass Energy (kJ/g)	19	19
P content in Biomass (%)	5	5
N content in Algae (%)	7	7
Electricity Price ($/kWh)	0.06	0.06
Electricity for P Removal (kWh/g-P)	0.95	0.37
Electricity for N Removal (kWh/g-N)	0.36	0.14
Electricity cost per lb P Removal ($/lb)	25.8	10.1
Electricity cost per lb N Removal ($/lb)	9.9	3.9

Tank Cost. The tank body of the Baseline Design for the algal nutrient- removal system is estimated as a 10-ft depth circular clarifier. The circular clarifier is a cast-in-place concrete structure with a sloped bottom, a sludge-rake mechanism, and a center rake-type sludge collector. Designed as an up-flow clarifier, it has a central inlet line and an interior channel with a fixed weir around the perimeter wall to receive processed water. For a 100 MGD capacity plant, ten clarifiers (35,000 ft^2 floor area each) were needed. The cost estimation is based on "Cost Accounting and Budgeting for Improved Wastewater Treatment" (USEPA, 1998). The equation used to estimate the clarifier cost is shown below, and the 1998 costs generated by this approach were then adjusted to 2018 costs as described earlier:

$$Clarifier\ Cost\ (1998\ \$) = 3470.6\ \times Floor\ Area\ (ft^2)^{0.6173}$$

LED Unit Cost. LED units allow the algae cultivation system to treat wastewater within a significantly smaller footprint. At the current Baseline Design, the LED units are spaced 2-ft apart from the other units, which would require 90,000 LED units for a 100 MGD system. The LED units consist of three major cost components: (1) LED strips, (2) Power supply and control units, and (3) LED glass tube and cooling fans. Each LED strip (1 ft) has five red LEDs (XPEPHR-L1-0000-00901, 650 nm) and one blue LED (XPEBRY-L1-0000-00P01, 435 nm). High power LEDs were chosen to maximize photon output for higher algae growth. Each LED unit has an 8-ft depth into water, which leaves 2 ft from the bottom to allow biomass harvesting. Each LED unit illuminates in four directions; therefore, four rows of LED strips are needed. A total of 32 ft of LED strips is installed in each LED unit. The current commercial price for a high-powered LED strip is $45/ft. After consulting with LED vendors, a 0.6 multiplier can be applied to the cost estimation for mass production on the scale estimated here. Therefore, the LED strips would cost $864 per LED unit.

LED units require an individual power supply and controller for flashing and intensity changes. A 24 V DC power supply (LRS-350-24) and flashing control module are estimated to cost $72/unit for a mass order. Three-inch diameter glass tubes with a central aluminum LED mount and cooling fan were quoted at $180/10ft (Wilmad-Labglass, NJ) and $20/unit (LED supply, VT). Once again, a 0.6 multiplier is applied to the cost estimation for a mass order.

The major operational cost for LED units is the electricity usage. In this analysis, LED electricity cost was estimated based on the P-removal target. As shown in Table 7, for the current technology, 0.95 kWh is consumed per gram of P removed. The LED energy consumption can be reduced to 0.39 kWh/g-P, based on the better LED efficiencies that are available today as mentioned earlier.

Other Miscellaneous Component Costs. Other important components of the LED-enhanced fixed-film algal nutrient-removal system include plastic media, water pumps, and gas-feed blowers. The media is important for biofilm development and retaining biomass in the system. Anox^{TM} K5 disk-shaped media (Veolia, Paris) were selected as the biofilm growth media used in this study. The K5 media is made of extruded HDPE with the density of 0.95 kg/m^3, diameter of 25 mm, and a thickness of 5 mm, which provided 800 m^2/m^3 of protected surface area for biofilm growth. In the previously discussed experiments, a 20 percent filling ratio was determined to be the most effective value. Thus, for a 100 MGD plant, 190,000 m^3 of K5-media are required for a 20 percent filling. The vendor provided the price range between $500 to $1,000/m^3, and we assumed $500/m^3 in this study. Thus, the total estimated cost for the plastic media will be $9,500,000.

A feed-pump station is often necessary to lift the water higher than the source of supply so that the treatment processes have sufficient gravity flow to overcome the head loss of the downstream process and provide sufficient water to meet demand. This is usually a high-flow, low-head pumping requirement to lift the water 20 to 30 ft. The cost estimation is based on "Cost Accounting and Budgeting for Improved Wastewater Treatment" (USEPA, 1998). The equation is shown as follows:

$$\mathit{Pump\ Station\ Cost}\ (1998\$) = 12169 \times \mathit{Capacity}\ (\mathit{MGD}) + 60716$$

Aerators not only provide the major means of mixing the plastic media but also allow for occasional sparging to clean the LEDs and facilitate biomass harvesting. Based on the previous study, 20 cfm are sufficient to provide enough aeration for mixing and sparging in a 20 ft^2 surface area tank. Therefore, for the 100 MGD system, a 350,000 ft^2 surface will requires at least 350,000 cfm of aeration. Bolles (2016) developed a model to calculate the horsepower requirement for a wastewater aeration system based on adiabatic compression:

$$P_w = \frac{WRT_1}{550 \times n \times e}\left[\left(\frac{p_2}{p_1}\right)^{0.283} - 1\right]$$

where, P_W = power requirement of each blower (hp)
W = mass flowrate of air (lb/s), 402.5 lb/s
R = engineering gas constant for air 53.3 (ft-lb/(lb air)*°R

T_1 = absolute inlet temperature (°R = 460 + °F), 537 °R
p_1 = absolute inlet pressure (lb_f/in^2), 14.7 lb_f/in^2
p_2 = absolute outlet pressure (lb_f/in^2), 18.7 lb_f/in^2
n = 0.283 for air
550= ft-lb/s-hp
e = efficiency, assumed 80 percent

Using this equation, a total of 6,500 HP blower is needed for the target 100 MGD system. Sedlak (1991) estimated that the cost of aeration equipment is $750 per horsepower. Therefore, the cost of an aerator will be $4,875,000 (1991 dollar basis), which was adjusted to 2018 costs as described earlier.

Total Suspended Solids Removal System and Costs

In the lab-scale experiments discussed earlier, we identified that integration of the downstream TSS-removal process is essential. In this study, we selected pH-induced flocculation as the TSS removal process as a baseline because it was tested, and it is used in commercial algae cultivations.

Biomass flocculation is initiated when the pH is raised to 10 – 11, where a chemical ion starts to precipitate with algal biomass and begins settling. Our previous study showed that a four-hour settling time at pH 10 can drop effluent TSS values to less than 10 mg/L. Therefore, the TSS-removal process used in this study includes four-hour HRT clarifiers and chemical storage and chemical dosage equipment.

The cost of the clarifier for removal of excess TSS was estimated using the same equation mentioned in the algae tank section. The only difference is the HRT of the tank was reduced to four hours. Sodium hydroxide is a common chemical used in wastewater treatment for raising pH. It requires a secondary containment separate from other reactive chemicals, and its major sub-system components include: storage tanks, transfer pumps, metering pumps, piping and valves, and the facility enclosure. Our cost estimate for this sub-system is based on "Cost Accounting and Budgeting for Improved Wastewater Treatment" (USEPA, 1998), using the following equation, which was then inflation adjusted to 2018 costs:

$$\begin{aligned}&\mathit{Sodium\ Hydroxide\ Sys.\,Capital\ Cost}\ (1998\$)\\&\quad = 118.68 \times \mathit{Feeding\ rate}\left(\frac{gal}{day}\right) + 38701\end{aligned}$$

Sodium hydroxide is usually delivered and stored in liquid form at 50 percent. For a 100 MGD plant, a 1440 gal/day feeding rate is needed to raise pH to ten and induce flocculation. The unit cost for sodium hydroxide is $0.7605/gal (City of Wichita Falls, 2015).

After the TSS-removal process, the WWTP has to adjust effluent pH back down before discharge. Sulfuric acid is commonly used in the wastewater industry to adjust pH and is delivered in liquid form at 93 percent. Its storage and feed requires separate containment protection from other reactive chemicals. The USEPA (1998) provides the following cost estimation equation for this required system, which was adjusted to 2018 dollars:

$$\mathit{Sulfuric\ Acid\ Sys.Capital\ Cost}\ (1998\$) = 32.606 \times \mathit{Feeding\ rate}\ \left(\frac{gal}{day}\right) + 26395$$

For a 100 MGD plant, 950 gal/day feeding rate is needed to adjust effluent pH back to seven for discharge. The unit cost for sulfuric acid is \$2.6/gal (City of Wichita Falls, 2015).

Biomass Dewatering Cost

After the biomass is harvested from the reactors, it has to be dewatered in order to be sold as a commodity. A belt filter press is considered to be a more economically favorable route in comparison to other dewatering methods such as DAF or centrifugation for algal biomass (Beal et al., 2015). The filter press units receive algae directly from the clarifier at 1 percent (dry weight, [d.w.]) and concentrates the material to 20 percent (d.w.), with 98 percent separation efficiency. The power demand for the filter press is 0.3 kWh/m^3 of algal slurry into the filter press. The NREL (2016) reports the installed capital cost of a filter press can be calculated by the following equation:

$$\mathit{Filter\ Press\ Capital\ Cost}\ (\$2016) = 70 \times \mathit{slurry\ process\ rate}\ \left(\frac{m^3}{day}\right)$$

where, slurry solid content is 1 percent (d.w.). In this study, the daily algal slurry is estimated to be 1140 m^3/day.

Operating and Maintenance Cost

Operating costs and assumptions for the LED-enhanced algal nutrient-removal system are given in Table 8. Labor costs are taken from Dutta et al. (2011) and converted to a 2018 dollar basis. Although labor costs are highly sensitive to local conditions, the estimated labor cost is less than 5 percent of the overall O&M cost. Thus, the uncertainty of labor cost has a negligible impact on the overall O&M cost.

The largest contributors to the annual O&M cost are LED electricity usage (43 percent) followed by capital replacement (18 percent). In our previous experimental work, we estimated 0.48 ~ 0.95 kWh electricity is required to remove 1 gram of P. There are several ways to further improve the electricity efficiency for P removal. One way is to use an optimized flashing frequency, which can increase photosynthetic efficiency and therefore reduce the amount of electricity energy needed. Researchers are also developing new LED with a higher electron-photon conversion ratio. The commercially available LED's electron-photon conversion ratio has been improved from 50 percent to 80 percent in just the past three years, and it is expected to further improve over the next 10 - 15 years. The high capital replacement cost is the combined result of LED lifetimes and high LED costs. The typical lifetime for current LEDs is between five to ten years, which is also expected to improve in the next 15 years (DOE, 2009).

TABLE 8: OPERATION AND MAINTENANCE COSTS FOR EXPANSION UNITS

	Expansion Operating and Maintenance Cost			
	Number of Personnel	Hours per Year	Hourly Rate	Annual Cost (2018)
Labor Cost				
Operation/Maintenance Labor	16	2080	$20.70	688,896
Operation Supervisor	1	2080	$31.25	65,000
Labor Benefits (30%)				226,169
Sub-Total Labor Cost				980,065
Reagent Usage	Treatment Flow Rate	Unit Cost		Annual Cost (2018)
Sodium Hydroxide Feed (50%)	1440 gal/day	$ (2015) 0.7605/gal		418,116
Sulfuric Acid Feed (93%)	950 gal/day	$ (2015) 2.6/gal		943,044
Sub-Total Reagent Cost				1,361,160
Maintenance		Routine Maintenance	Capital Replacement	Annual Cost (2018)
Total Capital ($230,870,063)				
Routine Maintenance		1%		2,308,706
Capital Replacement			1.5%	3,463,060
Sub-Total Maintenance Cost				5,771,766
System Energy	kWh (annual)	Price	unit	Annual Cost (2018)
Electric Power - LED	148,405,231	0.055	$/kWh	8,162,288
Electric Power - Aeration	42,460,158	0.055	$/kWh	2,335,309
Electric Power - Filter Press	124,830	0.055	$/kWh	6,866
Nature Gas for Drying	41,951	2.99	$/MMBTU	125,434
Sub-Total Energy Cost				10,629,896
Total Annual O&M Cost				**18,742,887**

Overall Cost

Expansion Capital Cost. As described in Section 2, the proposed WRF expansion system includes three major components: a LED-enhanced, fixed-film algae nutrient-removal reactor, a TSS removal unit, and biomass dewatering. Table 9 shows the details of the expansion unit capital cost. The LED units (include strips, power supply, control, glass, and fan) is the largest contributor, which accounts for 55 percent of the total process cost. LED strips are the major cost within the LED units. This result highlighted that the major technical challenge for this study is the economics of the LEDs. Improvements in LED costs, life span, and energy efficiency will significantly reduce the cost of nutrient removal.

The main algae tank and TSS clarifier are the second and third highest contributors of the overall capital cost (16 percent and 13 percent). Although it may not be as significant as LED improvements, reducing the tankage footprint or system HRT can improve the proposed system's economics.

Annualized Unit Cost. The annualized capital costs and annual operating and maintenance costs were normalized by dividing by the mass of nutrient removal from the whole plant. These normalized costs became the Unit Capital Cost and Unit operating and maintenance cost. As shown in Figure 21, annualized unit capital cost, unit O&M cost, and feed revenue for P removal are calculated as dollars per lb of P removal. The annualized unit capital cost for P removal is $7.50/lb in the Baseline Design Condition, while the unit operating and maintenance cost for P removal is $7.20/lb. The feed revenue is calculated by multiplying the annual biomass production by the animal feed selling price (up to $2,000/ton). The costs and revenue were split evenly between N and P removal functions. The result shows selling algal biomass as feed can offset $2.70 per lb of P removed, which made the life-cycle cost for P removal $12.00/lb. Considering the P removal unit cost for other biological nutrient removal technologies is generally between $2.5 to 12/lb P removal, the proposed system would have difficulty competing with other technologies at the current stage of development. There is a need to develop advanced strategies for reducing the Baseline System costs.

Integration of Different Cost-Saving Strategies

Three cost-saving strategies have been developed to reduce the P removal unit cost for the LED-enhanced, fixed-film algal nutrient-removal system.

Dropping LED Costs Over the Next Decade. In the annualized unit-cost analysis, the LED units account for 55 percent of the total equipment cost and 43 percent of the O&M cost. Since the LEDs are the major cost contributor, LED technology improvements will have the most impact on the overall unit cost. The U.S. Energy Information Administration published a future LED cost forecast in their 2014 Annual Energy Outlook (USEIA, 2014). As shown in Figure 22, the price of LEDs is projected to drop significantly over the next 10 - 12 years.

TABLE 9: TOTAL EXPANSION CAPITAL COST

Expansion Capital Cost (100 MGD)					
Process	Cost Based	Unit Size	Unit Cost	Number of Process Units	Total Cost (2018)
LED Enhanced P Removal Reactor					
Main Tank	\$ (2007) = 3,470X^0.6,173, X = Basin Area (ft^2)	35,000 ft^2	2,215,046	10	28,217,142
LED Strip	\$27 / ft	32 ft per unit	864	90,000	77,760,000
LED Power Supply and Controls	\$72 / unit	1	72	90,000	6,480,000
LED Glass tube and Cooling	\$120 / unit	1	120	90,000	10,800,000
Feed Pump	\$ (2007) = 1,2169X + 60719, X = Pump Capacity (MGD)	100 MGD	1,492,388	1	1,901,131
Media	\$500/m3	1,900	950,000	10	9,500,000
Blower	\$(1,991) 750* X, X=Horsepower	650 hp	487,500	10	10,857,461
TSS Removal - Autofloccultion					
Clarifier @4 h HRT	\$ (2007) = $3,470X^{0.6173}$, X = Basin Area (ft^2)	35,000 ft^2	2,215,046	8	22,573,717
Sodium Hydroxide Feed (50%)	\$ (2007) = 118.68X + 38,701 X = Feed in gal/day	1,440 gal/day	209,600	1	267,007
Sulfuric Acid Feed (93%)	\$ (2007) = 32.606X + 26,395 X = Feed in gal/day	950 gal/day	57,371	1	73,084
Biomass Dewatering					
Filter Press	\$ (2016) = 70 X, X = m^3/day @ 1% solid content	1,140 m3/day	79,800	1	83,039
Drum Dryer	\$ (2011) 532.9 X, X= dry ton	4,161 ton/yr	2,217,397		2,502,705
			Sub Total Process Cost		171,015,285
			Yard Piping (10%)		17,101,529
			Site work Landscaping (5%)		8,550,764
			Site Electrical & Control (20%)		34,203,057
			Total Construction Cost		230,870,635
			Engineering, Legal, Administrative Cost (35%)		80,804,722
			Total Capital Cost		**311,675,358**

FIGURE 21: ANNUALIZED UNIT CAPITAL COST, UNIT OPERATING AND MAINTENANCE COST, AND FEED REVENUE FOR PHOSPHORUS REMOVAL

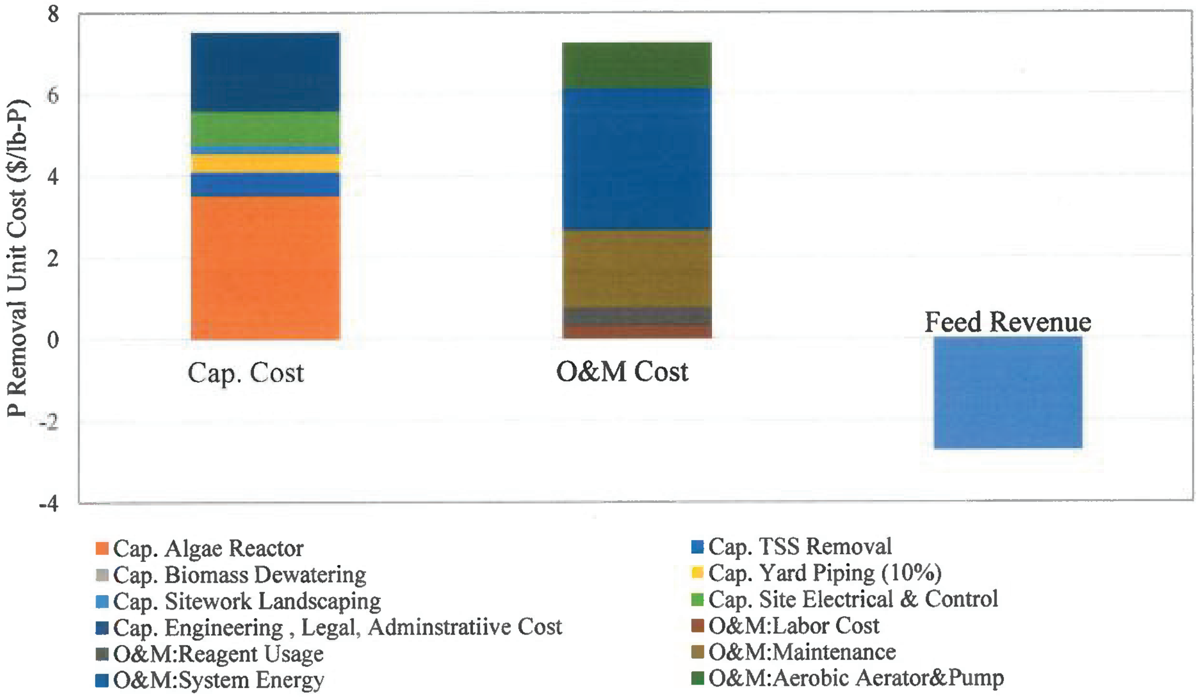
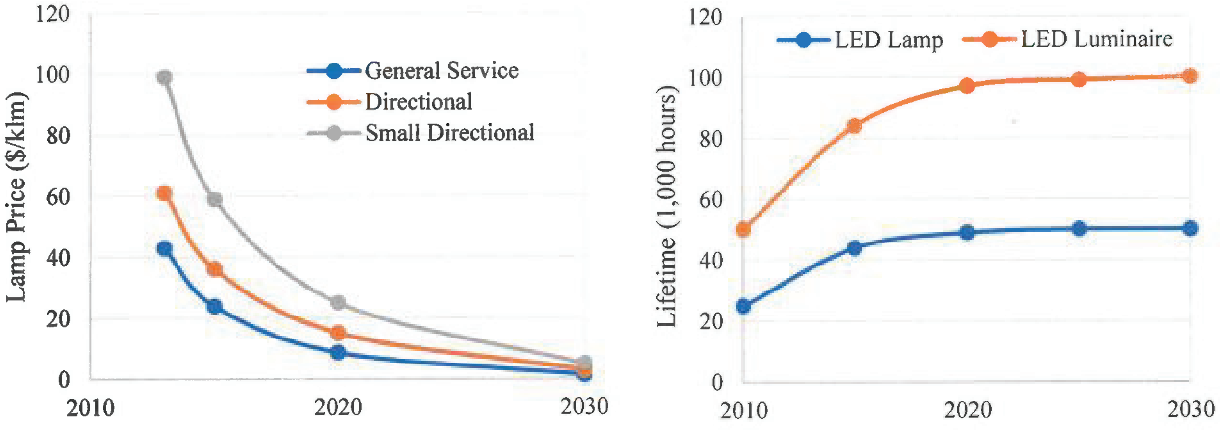


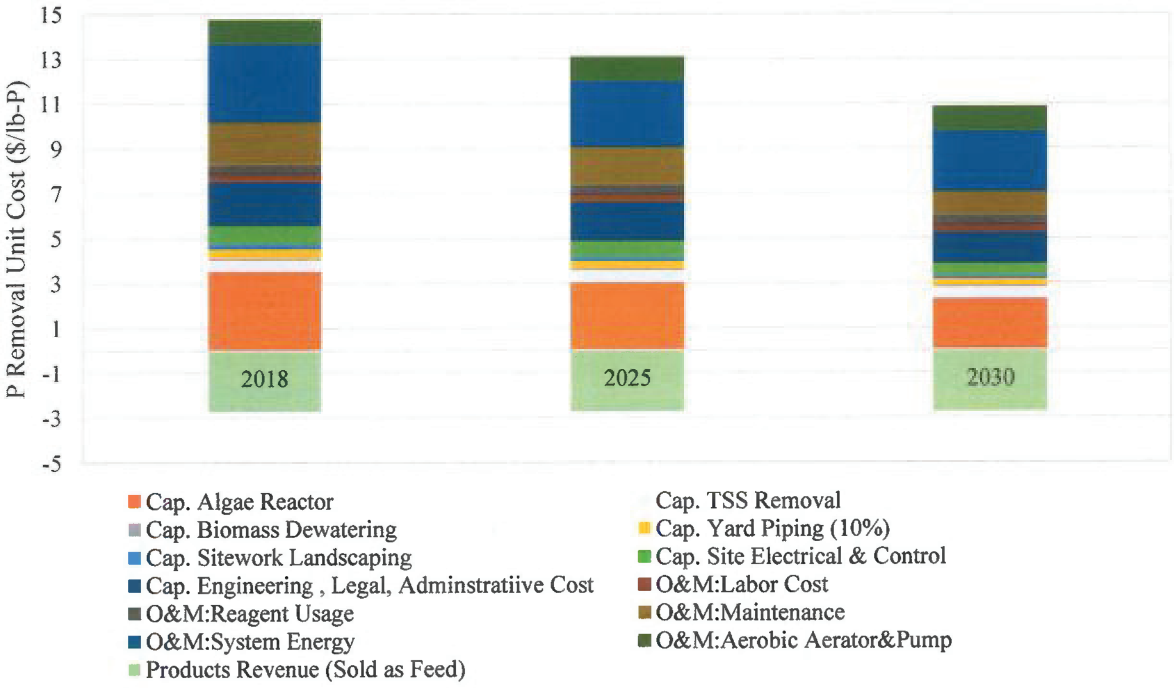
FIGURE 22 PROJECTED LED LAMP COSTS AND LIFETIME



In 2018, the price of a commercially available high-power LED is between 5~7 dollar/bulb (LED supply, VT), which agrees with the cost prediction of the EIA's 2014 report. Based on that forecast, both the price of the bulbs and their efficiency will continue to improve until approximately 2030.

Figure 23 presents the projected P removal unit cost over several years as LED technology improvements are realized based on the EIA forecast (2014). In 2018, 2025, and 2030, the life cycle unit cost for P removal is \$14.7, \$13.1, and \$10.8/lb-P. If the feed revenue is considered, the life cycle unit costs become \$12.0, \$10.4 and \$8.1/lb-P, respectively. All in all, the expected LED cost reductions of 67 percent would correspond to a 27 percent reduction in P removal unit costs between 2018 and 2030. It is obvious that the proposed LED algal treatment system will become much more favorable as LED technology advances and prices drop.

FIGURE 23: PHOSPHORUS REMOVAL UNIT COST OVER YEARS WITH LED TECHNOLOGY IMPROVEMENTS



Increasing Solar Light Inputs. Another approach to reduce the overall unit cost is to increase the system's surface footprint to allow more solar energy input and thus reduce the amount of LEDs needed for algae growth. However, this strategy requires a trade-off between land requirements and LED costs, and it may not be a desirable trade-off for all WRPs.

In order to evaluate the potential savings for solar energy inputs (E_{Solar}), we first calculated the energy requirement ($E_{Biomass}$) for the amount of algal biomass growth that have sufficient P uptake to achieve the target P removal at 100 MGD plant. Then the energy that needs to be provided from LEDs (E_{LED}) can be calculated using this equation:

$$E_{LED} = E_{Biomass} - E_{Solar}$$

where,

E_{LED} is the harvested energy provided by LED
$E_{Biomass}$ is the total harvested energy to support algae growth for P removal
E_{Solar} is the harvested energy from solar, which can be represented by:

$$E_{Solar} = W_{Solar} \times P_{Solar} \times A$$

where,

W_{Solar} is the average daily solar energy input, 3.9 (kWh/m^2/day) for Chicago, IL
P_{solar} is the solar photosynthetic efficiency, assumed to be 3 percent
A is the reactor surface area receiving solar input (m^2)

As described in Section 2, the LED unit in the proposed system was designed to rely purely on LEDs to provide light energy for algae to grow. Figure 24 shows the harvested energy source for different system footprints, ranging from 350,000 ft^3 to 1,400,000 ft^3, which represents 10 to 2.5 ft of tank depth. The results show that at the default footprint (10 ft depth), 10 percent of the harvested energy requirement can be offset by solar input. When the footprint is doubled or quadrupled from the default case (tank depth changed from 10 to 5 ft and 2.5 ft), 19 percent and 38 percent of the harvested energy requirement can be offset by the solar energy input.

FIGURE 24: TANK AREA AND HARVESTED ENERGY SOURCE DISTRIBUTION

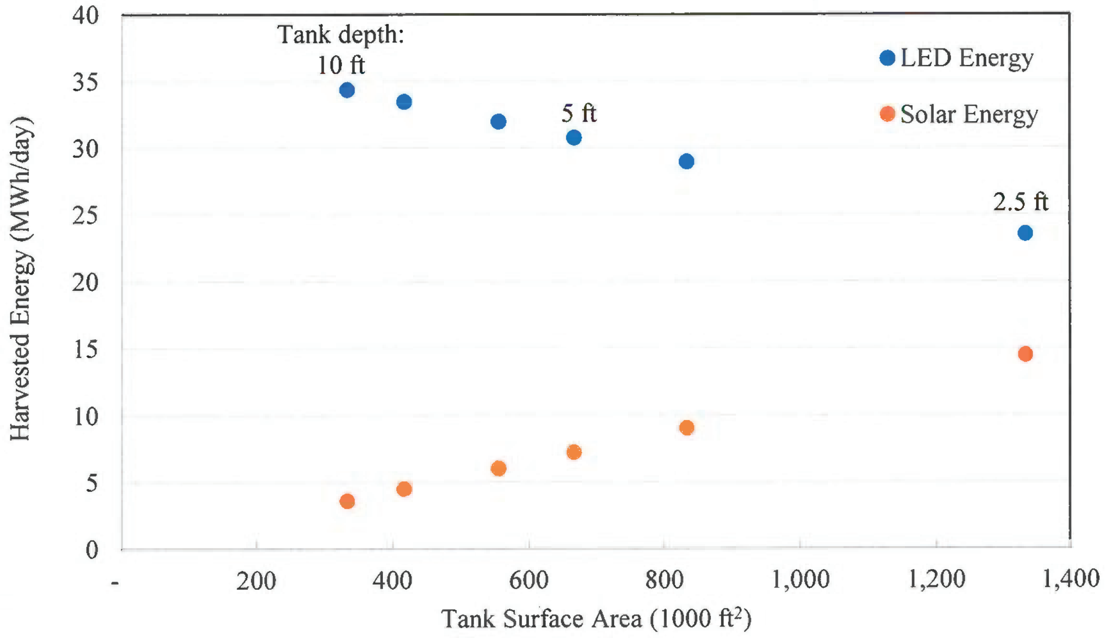
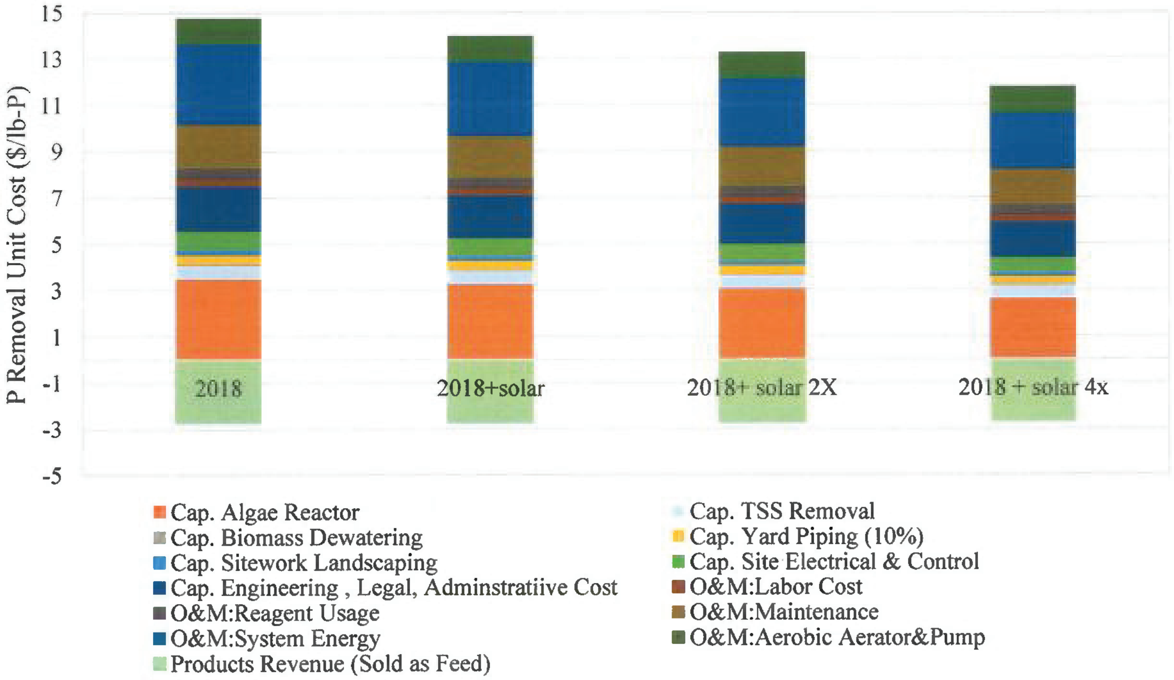


Figure 25 shows the P removal unit cost changes with the size of the algae process footprint when taking solar energy inputs into account. The cost estimation was done based on the projected energy savings for the solar input and then applying the same savings factor to the capital cost of LED units and the LED O&M cost from the Baseline Design case. All the other capital and O&M costs would remain essentially the same as the system's footprint increased. This study also

FIGURE 25: PHOSPHORUS REMOVAL UNIT COST FOR SYSTEMS WITH SOLAR ENERGY INPUT AT 1X, 2X AND 4X FOOTPRINT



assumed the WRP already owns the extra land area, and the land costs are excluded from this analysis.

The P removal unit cost for the 2018 Baseline Design case (no solar input) is $14.75 /lb-P before taking product revenue into account. The P removal unit costs for 1X, 2X and 4X footprint with solar energy input are $13.96, $13.25 and $11.75/lb-P before product revenue, which is a reduction of 5.3 percent, 10.1 percent, and 20.4 percent of the P removal unit cost when compared to the baseline case. When the footprint expanded to 15.3 (2X) and 30.6 (4X) acres from the initial 7.7 acres (1X solar), the total capital cost reduced $8,550,000 and $26,120,000, which means each acre of solar input saved $1,160,000 of total capital cost. It is important to note that solar light input vary with location and weather, but the potential savings from increasing solar input can indeed reduce the unit cost of P removal significantly. However, LED units are still essential for keeping the treatment performance steady.

Total Suspended Solids Removal With Cloth Filter

A final recommended method for reducing P removal unit costs is to replace the TSS removal process. The pH induced flocculation with a tertiary clarifier accounts for 13.4 percent of the total process cost and the reagent costs account for 7.3 percent of the O&M cost. Recent developments in cloth filtration processes have shown that it can be an economically favorable alternative for the tertiary TSS removal process. Cloth filters use specially designed cloth to filter the wastewater rather than sand or other granular media. The cloth panels are installed vertically inside a steel or concrete tank. Solids accumulate on the outside of the cloth panels, while filtered water is collected on the inside of the panels and directed to the effluent chamber. The solids on the outside of the cloth form a mat, and the water level in the filter rises. When the water reaches a preset level, the filter is backwashed by liquid suction. The cloth filters are rotated during the backwash process. Cloth filters can operate at a higher hydraulic loading rate than granular media filters, resulting in a smaller footprint. For example, Aqua-Aerobic Systems, Inc. has developed the Aqua MegaDisks Cloth Filter units with 2~3 µm pore size that is capable of tertiary TSS removal and algal biomass harvesting. For a 100 MGD plant, 14 of the largest Aqua MegaDisk Cloth Media Filters are needed. The vendor provided a preliminary budget price of $13,000,000 for 100 MGD units, including freight and installation supervision.

Figure 26 shows the P removal unit cost with a different TSS removal process. The year 2018 is the baseline case for which the LED cost is quoted in 2018 and integrated with pH induced flocculation in tertiary clarifier. The 2018 CF is similar to the baseline case; the only difference is the TSS removal process switched to a cloth filter. The P removal unit cost is reduced from $14.75/lb-P to $13.7/lb-P before the feed revenue, which is 7.1 percent of cost reduction. Considering that a cloth filter provides the ease of operation at lower cost and smaller footprint, it is more favorable than pH induced flocculation.

Cost Analysis of the Advanced Design Condition

Previous sections provided three readily available strategies to reduce P removal unit costs. In this section, these three strategies are combined together to form the Advanced Design Condition, and a cost estimate for this combination is provided. The Baseline Design Condition (2018), which includes LED costs as quoted in 2018, a pH-induced auto flocculation process for TSS removal and a system with all LED lighting that minimizes the process footprint (350,000 ft^2), was used as a reference for all comparisons. Then, we considered solar energy input for the baseline condition (2018+solar). Next, we changed the TSS removal process from a tertiary clarifier to a cloth filter (2018 CF Solar). Finally, we expanded the system footprint by a factor of up to 4X (2018 CF Solar 4X) for extra solar energy input, which reduced LED capital and O&M costs. Lastly, projected LED costs and efficiency reductions through 2030 were used to forecast the P removal unit cost at quadruple footprint with a cloth filter (2030 CF Solar 4X) to explore the lowest possible P removal unit cost of the proposed LED-enhanced, fixed-film algal nutrient-removal system.

The cost analysis for the Advanced Design Condition is summarized in Figure 27, which shows that the P removal unit cost for the 2018 Baseline ($14.75) can be reduced to $8.59/lb-P, with the Advanced System without any product revenue. The unit cost is reduced from the 2018 Baseline System of $12.02 to $5.86/lb-P with the Advanced System if animal feed product revenue was also considered. Since the LED is the major cost factor, the expected price drop of the LED by 2030 had the most impact on the P removal unit cost. Among the annualized capital costs and O&M costs, the algae reactor and system energy costs are always the top two cost components. The major components of the Algae reactor are the Tank and LED units. If the lower system HRT can be achieved, the P removal unit cost can be further reduced by reducing tankage volume. The system's HRT is limited by the algal biomass density in the system and the algae growth rate. In order to retain more algal biomass in the system, more media with higher surface area

FIGURE 26: PHOSPHORUS REMOVAL UNIT COST WITH TWO DIFFERENT TOTAL SUSPENDED SOLIDS REMOVAL APPROACHES, 2018 = PH INDUCED FLOCCULATION WITH TERTIARY CLARIFIER; AND 2018 CF = CLOTH FILTER

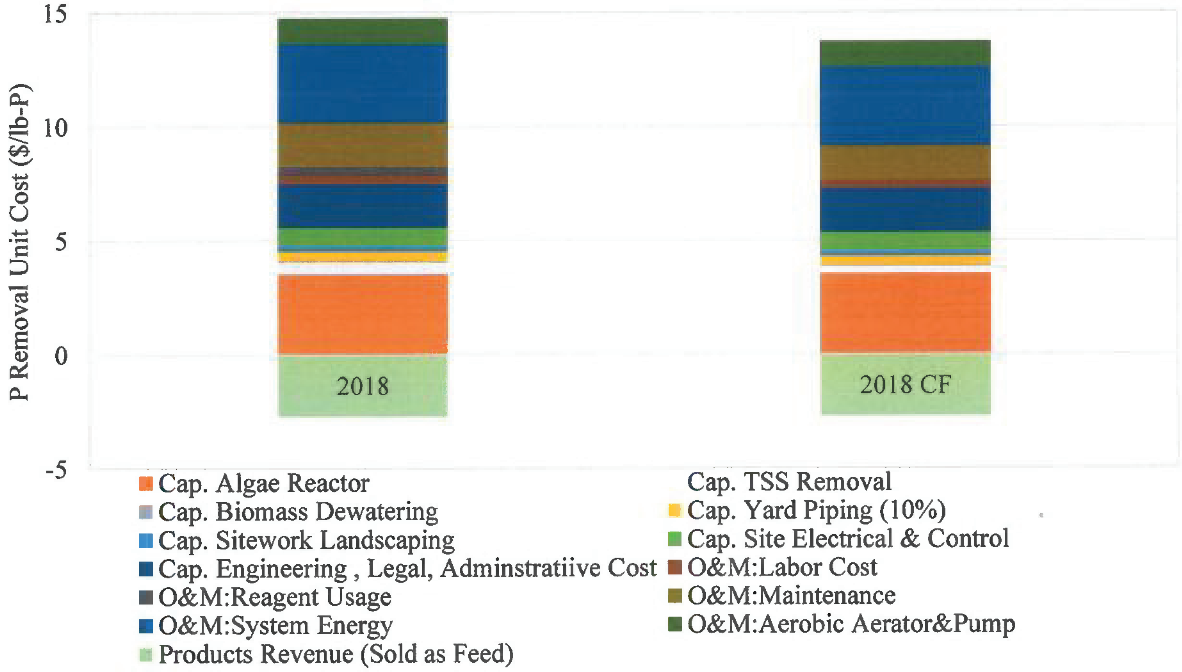
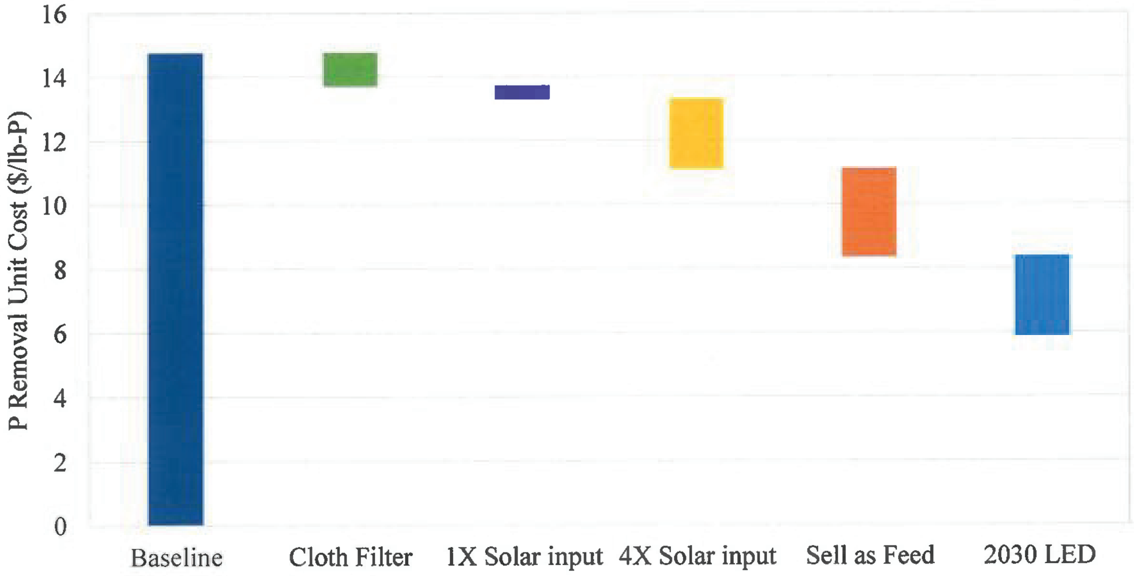


FIGURE 27: TECHNO-ECONOMIC ANALYSIS FOR THE ADVANCED DESIGN CONDITION COMBINING THREE COST-SAVING STRATEGIES



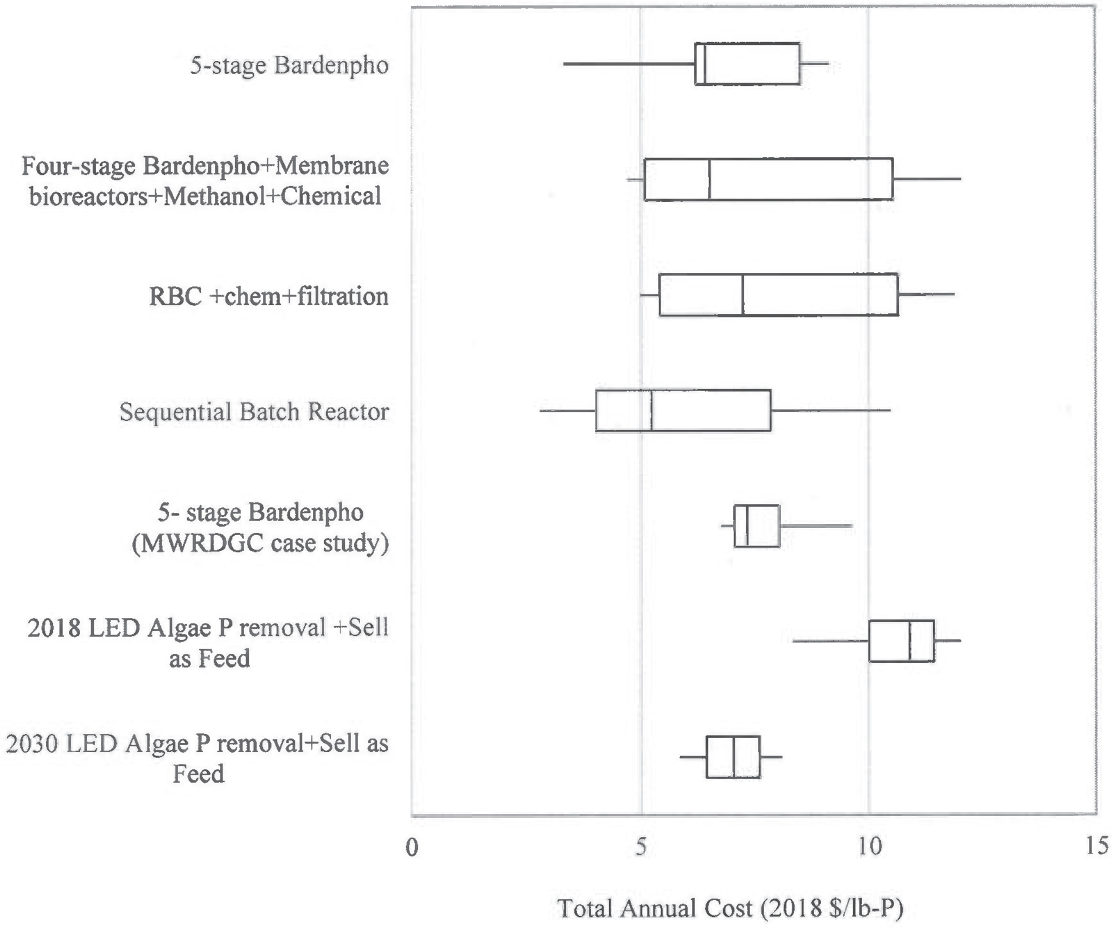
could be tested in the system. However, too much media in the system might pose challenges on the system's mixing and light delivery, which could negatively impact the algal growth rate. On the other hand, the system energy cost is dominated by LED electricity usage. The LED electricity usage is determined by the LED efficiency and algae photosynthetic efficiency. Higher photosynthetic efficiency requires less energy to produce biomass and uptake nutrients. There are many factors that can affect this efficiency, such as algae species, temperature, photon wavelength, and light-flashing frequency. Future studies should focus on optimizing the balance between the amount of media, mixing, and light delivery.

Comparison of Different Nutrient Removal Technologies Reported In Literature

In order to evaluate the economic feasibility of the proposed system, the nutrient removal technologies' unit costs were collected from a wide variety of sources (Hey et al., 2005; USEPA, 2008a; USEPA, 2008b; WaSDE, 2011; USEPA, 2015). This literature survey focused on the retrofit technologies that can achieve effluent TP level below 0.5 mg/L. Allocation factors were applied to the literature cost data in the same manner as described in the previous section for the P removal unit cost calculation. Figure 28 shows the range of P removal costs for different nutrient biological removal technologies from nine studies covering 26 different design cases. The P removal unit cost range between \$3 to \$12/lb-P for most of the nutrient removal technologies, and the average was \$7.1/lb-P.

The P removal unit cost for the Baseline 2018 LED algal system is at the higher end of the cost range when compared with existing biological nutrient removal technologies. Thus, at the current stage of development, the LED-enhanced algal nutrient removal system is less favorable than other technologies. However, when considering an Advanced Design Condition using three strategies for cost reduction (2030 LED algal system), the P removal unit cost is very competitive with other technologies, which warrants additional developmental work to pursue and prove out the Advanced Design Condition performance parameters.

FIGURE 28: COMPARISON AND RANGE OF PHOSPHORUS REMOVAL UNIT COSTS FOR DIFFERENT NUTRIENT REMOVAL TECHNOLOGIES



CONCLUSIONS AND RECOMMENDATIONS

The bench-scale experiments conducted at the UCSD have shown that an LED-lighted, fixed-film algae wastewater treatment system with integrated adsorbents removed an average of more than 60 percent of reactive P from secondary wastewater effluent with a six-hour HRT. On a concentration basis, the six hour HRT removed 1.2 mg/L of reactive or ortho-P on average and the effluent reactive P concentration was below 0.5 mg/L. Increasing the CO_2 concentration to 1 percent (v/v) was shown to further improve the P removal by approximately 10 percent. A photosynthetic efficiency of 16 percent was achieved when the lighting condition was 720 $\mu mol/m^2$-s with flashing at 100Hz. The fixed-film algal growth was also accompanied by a significant amount of suspended or sloughed algae that increased the TSS in the effluent from the algal treatment system. The pH induced auto-flocculation was also tested to accelerate biomass settlement. When the effluent pH raises to 10 by the addition of sodium hydroxide, it induced algal biomass auto-flocculation and reduced the supernatant TSS below 10 mg/L in four hours.

A TEA showed that the LED-enhanced, fixed-film algal nutrient removal system has the potential to be competitive with other nutrient-removal technologies. The estimated baseline P removal unit cost is \$14.75/lb-P or \$12.03/lb-P if the harvested biomass sold as animal feed. Three strategies were proposed for further reducing these unit costs: (1) use cloth filter technology for TSS removal, (2) increase the system footprint to allow more solar energy input, and (3) allow time for expected LED price reductions over the next 10 - 12 years. When all three of these strategies are combined into an Advanced Design Condition, the P removal unit cost would be reduced to \$8.59/lb-P or \$5.86/lb-P if product revenue was included. The system costs were dominated by the LED capital costs and the electrical energy costs to run the LEDs, which scale directly with the amount of P to be removed from the system. As a result, this system has less of an economy of scale than most other wastewater treatment processes, which have a larger percentage of costs in items such as piping, pumps, and tanks that have very strong economies of scale. As a result, a LED-enhanced algae nutrient-removal system is expected to be more advantageous in small to medium size wastewater applications. LED-lighted algae treatment would also be advantageous in polishing applications where the effluent nutrient limits are very low, but the total amount to be removed is smaller.

Future research in several key areas is recommended to support the Advanced Design Condition Targets, including:

- Further reduce P removal unit cost

  Improve photosynthetic efficiency by providing optimal LED wavelength combinations, flashing frequencies and intensity. Although red and blue wavelengths have been identified as the most effective wavelengths for photosynthesis, the optimal ratio between red and blue light is species specific. By studying the optimal red/blue combination and flashing frequency, the algal growth rate and the P uptake rate can likely be improved.

Shorten HRT to reduce tankage cost. By adding more media, more algal biomass can be retained in the system and nutrient removal can be faster. Micronutrients such as biotin thiamine or cooper can be added into the system to study the tradeoff between nutrient cost and improved growth rate.

- Product valuation

  Characterize harvested algal biomass. Identify the nutritional value of the algal biomass. Some pigments, such as phycocyanin, are found in certain algae species and can be quite valuable if extracted.

  Conduct animal feed tests. Algae is a common component of fishmeal diets. However, wastewater grown algae will likely experience heightened scrutiny from customers and regulators. Animal testing must be conducted to address potential concerns with toxicity and pathogens.

  Biofuel testing should also be conducted with the mixed algal biomass grown in the system proposed in this report.

- Conduct life-cycle analysis (LCA)

  cts. LCA should be conducted to evaluate environmental impacts of the proposed system. Although algae are well known for the ability of reduce CO_2 emissions, the carbon balance of the whole system may still be positive due to LED manufacturing processes and energy consumption. A comprehensive LCA is required to confirm the net environmental impacts.

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APPENDIX

PRELIMINARY DESIGN SPECIFICATIONS FOR A PILOT ALGAE TREATMENT SYSTEM AT THE METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO'S TERRENCE J. O'BRIEN WATER RECLAMATION PLANT

PRELIMINARY DESIGN SPECIFICATIONS FOR A PILOT ALGAE TREATMENT SYSTEM AT THE METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO'S TERRENCE J. O'BRIEN WATER RECLAMATION PLANT

Information from the bench-scale algal treatment systems, as presented in the previous sections, was used along with information from the scientific literature and commercial experience for planning and preliminary design of a larger pilot system to be installed at the District's O'Brien WRP. The design process was collaborative between staff from the District, UIUC and CDM that included a series of meetings during 2017 with the overarching goal to design a scalable pilot system that would be representative of potential future full-scale algal nutrient removal systems at the District. This section describes the major pieces of equipment included in the proposed pilot system, as well as recommended design criteria and specifications for the major items.

Summary Design Description

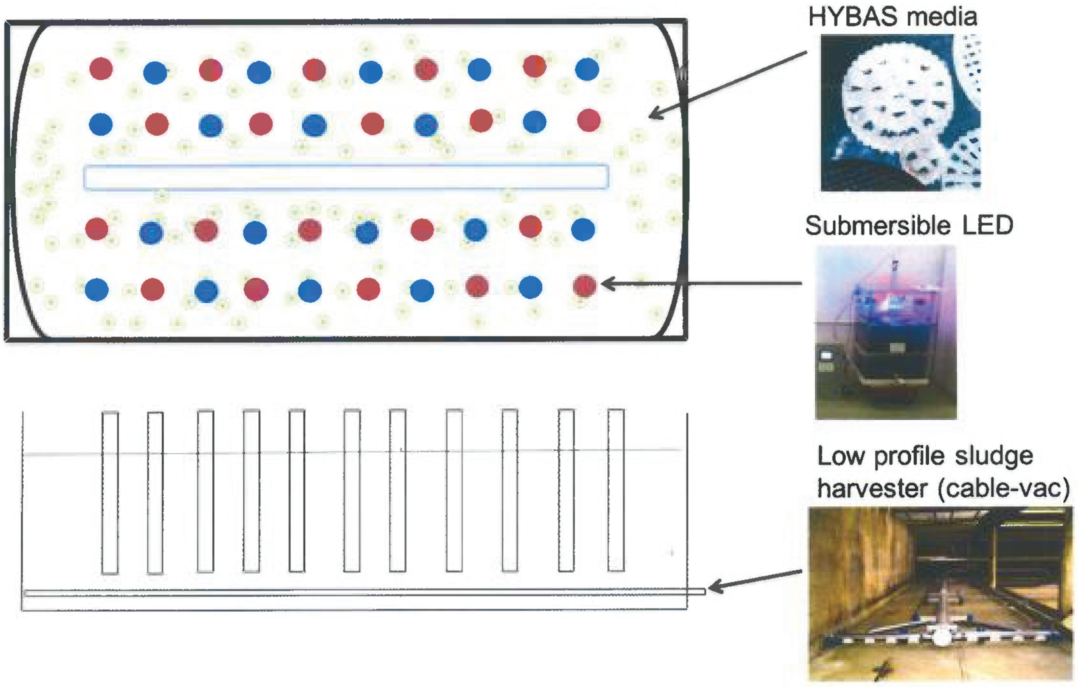
Some key aspects of the design of the algal wastewater treatment pilot system were discussed and decided at one of the early collaborative design meetings on February, 17, 2017. The selected design approach started with fixing the target volume of the system (~25,000 gallons) and then allowing for variation in the flow rate to achieve a target hydraulic retention time that would be decided by ongoing bench-scale studies. This approach allowed for progress to be made on the site preparation, tank selection, and the amount of media needed for growing the fixed-film biomass.

Figure 29 shows schematically the key design features of the proposed pilot system, which includes a raceway pond type configuration, which was chosen for the pilot reactor design that will have a recirculating-loop internal flow pattern and open top channels with vertical walls. This is the most common large-scale algae cultivation reactor configuration because of the relatively low construction cost, although typical raceways are very shallow to maximize solar lighting inputs. Another advantage of choosing a raceway pond configuration for this pilot project is that it will allow for the use of prefabricated shipping containers for the process tankage. This will reduce the time needed for implementation and allows for over-the-road transportation. Commercially available tanks will still likely require some customized modifications to accommodate all the desired design features such as a central tank divider wall, influent/effluent ports, and LED lighting installation.

Also shown in Figure 29, a floating plastic media is proposed for the pilot system to encourage attached growth algal biofilms that will allow the system to decouple the HRT and SRT. Therefore, the system is able to treat the mainstream wastewater flows at a faster rate without washing out the biomass. Jet pumps and air sparging are proposed for mixing and water recirculation within the tank and to provide the shear force needed to facilitate sloughing of the biofilm from the media. Sloughed biomass will be collected using a low profile, sludge collection mechanism that is commercially available.

Artificial LED lighting is also proposed to allow greater tank depths and more light to be delivered per square foot of the algae growing system than typical solar cultivation operations.

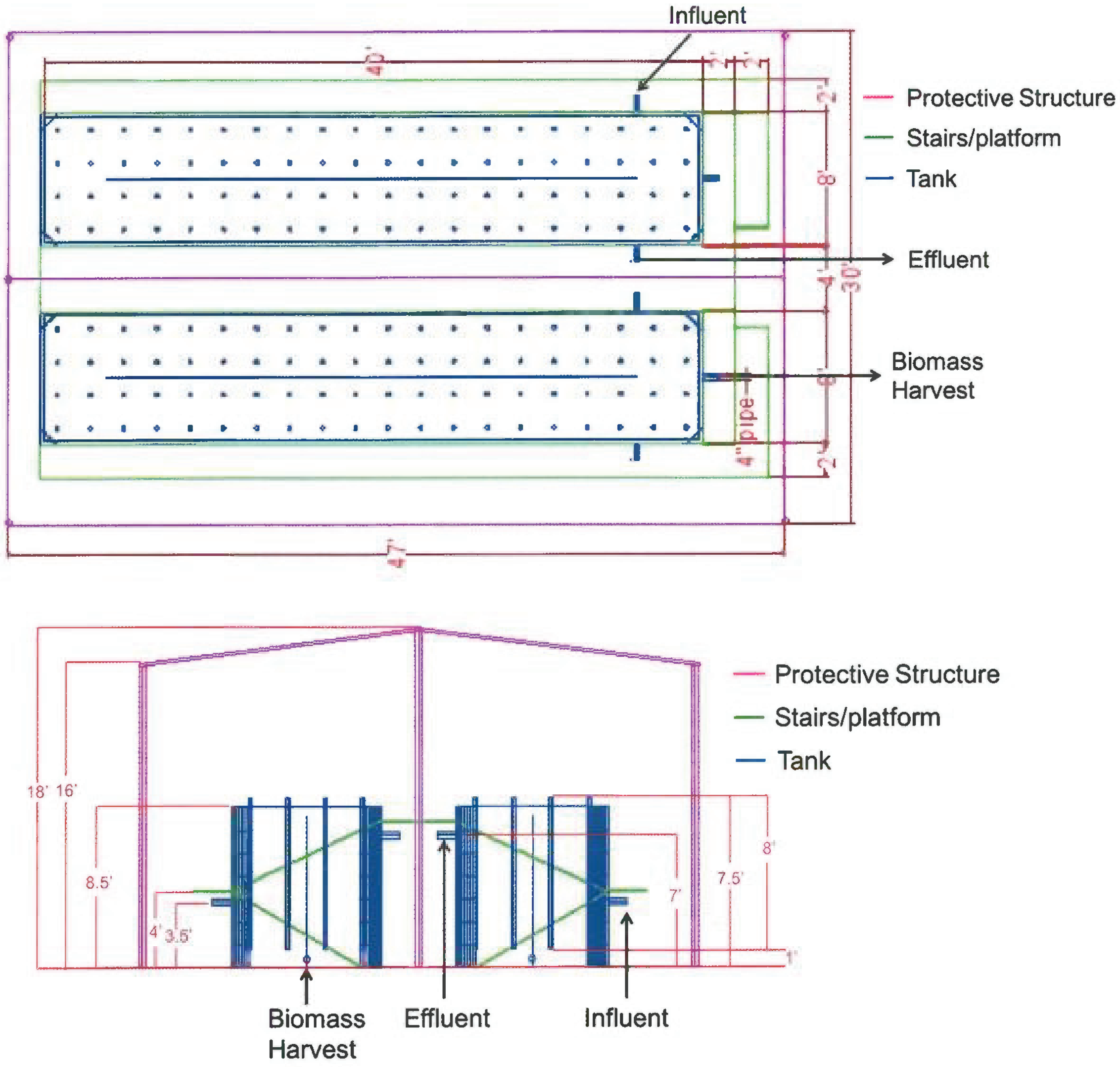
FIGURE A-1: SCHEMATIC TOP AND SIDE VIEWS OF PROPOSED PILOT ALGAL WASTEWATER TREATMENT SYSTEM, NOT TO SCALE, WITH PICTURES OF KEY DESIGN ELEMENTS



This will facilitate a significantly smaller footprint, but it will also increase the energy demands for the system in comparison to an exclusively solar illuminated system. However, in the District's case, the lower land requirement is generally considered to be a higher priority that justifies the additional energy for artificial lighting. Although this study was initiated with a higher value on reducing the footprint of the pilot system, future full-scale applications can revisit the tradeoff between land area and lighting energy inputs. The use of submersible LED lighting with primary wavelengths in the red and blue spectrum is recommended, corresponding to the primary absorption wavelengths of key photosynthetic pigments, which maximizes the energy efficiency.

Figure 30 shows the general layout drawings of the proposed pilot system design drawn to scale with a top view and a side view. Blue lines indicate the raceway tank components, which include two 40-ft shipping containers that will be set up to operate in parallel so the pilot system can provide a side-by-side comparison of different operating conditions. Central dividing panels allow a recirculating loop internal flow pattern. The LED units will be installed within the tanks with a series of frames that can be pulled out individually. Influent, effluent, and harvest ports are assigned on the east side of the tanks because the expected water source and discharge site are located on the east side of the systems. Green lines represent the stairs and platform designed to support maintenance activities and touring of the pilot system. Pink lines show the proposed overhead protective roof structure that covers the whole system.

FIGURE A-2: TOP AND SIDE VIEWS OF THE PROPOSED PILOT SYSTEM - TO SCALE



The recommended site for the pilot algae wastewater treatment system at the District's O'Brien WRP is shown in Figure 31, which is adjacent to a currently unused pump house. The overhead satellite image in this figure shows an overlay of two rectangular tank reactors in yellow cross-hatching to be located on the south side of the existing pump house. District staff is working on plans to bring electrical, wastewater influent, effluent, and non-potable water utility connections to this site. A wet-weather protection unit for LEDs and other electrical devices will be provided by an open overhead metal roof structure. On-site instrumentation will include a flow/pump operation system, temperature probe, DO probe, site camera, and light density probe. All the data will be stored on site and shared as needed with remote partners.

FIGURE A-3: PROPOSED SITE FOR PILOT ALGAE TREATMENT SYSTEM AT THE METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO'S TERRENCE J. O'BRIEN PLANT (A) PLAN VIEW WITH TANK FOOTPRINT IN YELLOW CROSSHATCHING AND (B) CROSS SECTIONAL VIEW ALONG THE SOUTH SIDE OF ADJACENT BUILDING

Preliminary Pilot System Equipment Budget and Proposed Procurement Methods

The following table (Table A-1) shows the estimated budget for the major equipment items. The total budget is $495,000, which doesn't include installation. The LED lighting units are the single largest cost item (46 percent), followed by the shipping container tanks (23 percent).

TABLE A-1: EQUIPMENT BUDGET ESTIMATE FOR THE PROPOSED PILOT ALGAL TREATMENT SYSTEM

Item	Unit Cost	Number	Total
Shipping container	$50,000 / tank	2	$100,000
Media	$1,000 / m^3	36	$36,000
Feed Pump	$2,000	3	$6,000
Aeration Pump	$1,000	3	$3,000
Jet Pump	$2,000	3	$6,000
LED units	$1,000 / unit	200	$200,000
Protective Structure	$24,000	1	$24,000
Sludge collection	$30,000	2	$60,000
On-site instruments	$3,000	2	$6,000
Total			$495,000

Different procurement approaches were discussed with District staff, but no firm recommendations were made. District staff asked to delay procurement activities to allow for review of the study results and their full-scale implications, with particular attention on the large electrical needs for the proposed LED-lighted algae-treatment system. If needed, the procurement approach can be broken down into two packages to accelerate the project's implementation schedule. The first procurement package could focus on site work, the protective superstructure, and setting of the process tanks. A second package would then handle the mechanical and electrical equipment systems to be installed in the tanks. The superstructure and tanks are prefabricated, metal structures that could be designed more quickly and implemented while the detailed design of the mechanical and electrical systems in the tanks is ongoing.

Pilot Algae Treatment System Equipment Specifications

This section provides the proposed equipment specifications for the proposed pilot algae-treatment system including the following major equipment components:

- Shipping container tank
- Fixed film growth media
- Feed pump
- Aeration pump
- LED lighting elements

The specification information provided includes key design criteria and example equipment selections with pictures and suppliers.

TABLE A-2: SHIPPING CONTAINER

	Metric	Unit	Target Value	Value Range	Notes
1	Width	ft	8		
2	Length	ft	40		
3	Height	ft	6'	6' ~ 10'	
4	Maximum Cargo Weight	lb	150,000	110,000 ~ 200,000	
5	Material		Painted Steel		
6	Tank Type		Open top		
7	Modifications				Corner post, Center dividing baffle, catwalk
8	Number of Tanks		2		
	Manufacturers				Geneva Equipment; Dragon Used Equip.; Environmental Tank & Container; Southern Frac LLC

TABLE A-3: FIXED FILM GROWTH MEDIA

	Metric	Unit	Target Value	Value Range	Note
1	Form		Webbed Disk Shape		
2	Diameter	Mm	25	10 - 30	
3	Thickness	Mm	4	3-5	
4	Protected Surface Area	m^2/m^3	800	>400	
5	Material		HDPE		Other floating plastics acceptable
6	Density	kg/m^3	0.95	0.93 – 0.97	
7	Service Life	Year	15	10 - 20	
8	Temperature range	^oF		32- 122	
9	Volume	m^3/tank			X% of shipping container (TBD)
10	Manufacturers				ANOXKALDNES Inc VEOLIA HeadWorksBio

ANOX K5-Media (ANOXKALDNES Inc.)

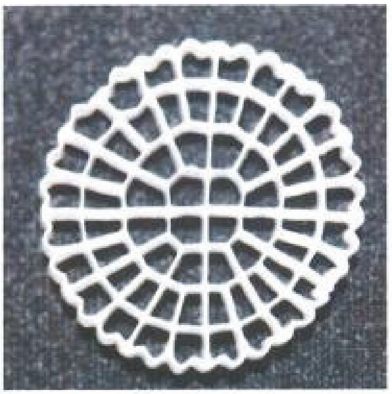
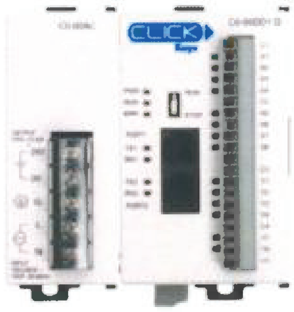


TABLE A-4: LED LIGHTING ELEMENTS

	Metric	Unit	Target Value	Value Range	Notes
1	Wavelength	Nm	450 (Blue) 650 (Red)	430 - 460 620 - 670	
2	LED power	mW	1,120 720		
3	Number of LED per ft per strip		6	6 - 8	
4	LED strip per ft		4	4 - 8	Single/double strip per side
5	Length of LED tube	Ft	5	4 - 6	
6	Control panel				Adjustable LED intensity
7	Submergible LED tube				
8	Number of LED				TBD
9	Power Supply		24 V		
10	Manufacturers				McMahon, LED Supply



LuxStrip - High power LED strip lighting (LED supply), $36/ ft

PLC control (C0-00AC, C0-00DD1-D, Click PLC), $98

Power supply (DRP-480-24, Mean Well), $112

TABLE A-5: FEED PUMP

	Metric	Unit	Target Value	Value Range	Note
1	Type of pump		centrifugal		Adjustable speed
2	Head	ft	>30		
3	Pumping rate	GPM	3.5- 28		2 h -16 h HRT for 20,000 gal tank
4	Horsepower		1	0.5-2	
5	Voltage	Volt	240	110-240	Site availability?
6	Max Pressure	psi	90	75 – 150	
7	Phase		3	1 , 3	Depend on voltage availability
8	Control Box				For speed control
9	Manufacturers				GOULDS Water Technology
10	Number of Units		3		2 duty and 1 shared standby

GOULDS CENTRIFUGAL PUMP, 3 HP, 208-230/460V (https://www.zoro.com/goulds-water-technology-centrifugal-pump-3-hp-208-230460v-2mc1h9a0/i/G6411870/)

TABLE A-6: AERATION PUMP

	Metric	Unit	Target Value	Value Range	Notes
1	Type of pump		Regenerative blower		
2	Head	ft	10	10-30	
3	Pumping rate	cfm	2,000	1,000-5,000	
4	Horsepower	hp	100	100-300	
5	Pressure	psi	10	5-15	
6	Control Box				
7	Manufacturers				Hoffman

HOFFMAN 732 Frame
Flow range: 600-3000 cfm
Pressure: 0.5-20psi
http://www.hoffmanandlamson.com/products/blowers-and-exhausters/multistage/60-hz/small-inlet/hoffman-732-frame/