OPTIMIZING PHOTOBIOLOGICAL TREATMENT OF REVERSE OSMOSIS CONCENTRATE

by

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LIST OF ABBREVIATIONS

Abbreviation	Description
TDS	Total Dissolved Solids
AWPF	Advanced Water Purification Facility
BWDF	Brackish Water Desalination Facility
RO	Reverse Osmosis
ROC	Reverse Osmosis Concentrate
NDMA	*N*-nitrosodimethylamine
NMOR	*N*-nitrosomorpholine
ED	Electrodialysis
EDR	Electrodialysis Reversal
NF	Nanofiltration
IPR	Indirect Potable Reuse
DPR	Direct Potable Reuse
OCWD	Orange County Water District
GWRS	Groundwater Replenishment System
SAWS	San Antonio Water System
E	Epivalve
H	Hypovalve
EC	Epicingulum

HC	Hypocingulum
PAR	Photosynthetically Active Radiation
RFM	Roy F. Mitte Building
LED	Light-emitting Diode
KBHDP	Kay Bailey Hutchison Desalination Plant
WRF	Water Reclamation Facility
CCRO	Closed-circuit RO
ECLWRF	Edward C. Little Water Recycling Facility
WBMWD	West Basin Municipal Water District
MGD	Million Gallons per Day

ABSTRACT

Water scarcity as an emerging concern worldwide highlights the importance of alternative water management and augmentation strategies. As one of the important water treatment technologies, reverse osmosis (RO) has been widely used in increasing number of brackish water desalination facilities (BWDFs) and advanced water purification facilities (AWPFs). However, lack of efficient and economical RO concentrate (ROC) managements, associated with RO scaling from elevated silica (SiO_2) and calcium raised challenges like permeation reduction and membrane scaling. In recent years, a diatom-based photobiological treatment has been studied to remove dissolved silica, calcium, nutrients, and other constituents from ROC prior to the secondary RO. Although the technical feasibility of the photobiological treatment has been demonstrated, no research was done to systematically study the impacts of light and temperature on the new process.

In this study, different parameters such as light temperatures, intensities and colors, illumination duration, and incubation temperatures were tested to optimize silica uptake rate in the photobiological treatment with brackish water diatom *Gedaniella flavovirens* Psetr3 and to produce more freshwater and reducing capital cost. ROC samples from Orange County Water District, Groundwater Replenishment System (OCWD GWRS, Fountain Valley, CA) and San Antonio Water System, H2Oaks Center (SAWS H2Oaks, San Antonio, TX) were used as model ROCs from AWPF and BWDF. Furthermore, the treatability of several other ROCs, applicability of using sunlight as a light source, and removal of *N*-nitrosamines, including *N*-nitrosodimethylamine (NDMA)

and *N*-nitrosomorpholine (NMOR) from OCWD GWRS ROC, were investigated in this research.

Light temperatures (2,700, 3,000, 4,000 and 5,000 K) did not impact silica uptake rate significantly. The difference between light colors (red, green, yellow, blue, and white) had no marked impact on SAWS H2Oaks ROC, but for OCWD GWRS ROC, the blue light resulted in a slightly higher (~28 mg/L/day) silica uptake rate than other colors (~23 mg/L/day). However, blue light bulbs were not recommended to use as a light source because the light output was approximately six times weaker than other colored bulbs. The photosynthetically active radiation (PAR) of 200 µmol m^{-2} s^{-1} was found to be sufficient for the photobiological treatment as the uptake rate was around 40 mg/L/day. The silica uptake was slower (30 to 35 mg/L/day) at lower PAR values (50 and 100 µmol m^{-2} s^{-1}). Intermittent light with 12 hours light and 12 hours dark did not slow down the silica uptake. The optimum temperature for the photobiological treatment was found to be 23 to 30 °C. The silica uptake was much slower at 10 °C, while the diatoms could not survive at a higher temperature (40 °C), which exhibited no silica removal.

Four additional ROCs were tested and confirmed the treatability with the diatom-based photobiological treatment, excluding the one from West Basin Municipal Water District, which has a high concentration of ammonia (310 mg/L as N) and known to be toxic for the diatom treatment in previous studies. The ROCs from the Closed Circuit RO at OCWD and Hamby Water Reclamation Facility (Abilene, TX) could be treated in three cycles with an average silica uptake rate of 33 mg/L/day (for both). Kay Bailey

Hutchison Water Treatment Plant (El Paso, TX) ROC was treatable repeatedly with a silica uptake rate of 31 mg/L/day with supplementary nutrients of 10 mg/L of nitrate-N and 5.5 mg/L of orthophosphate.

Unlike the experiments in the laboratory using LED as a light source at controlled temperature, the photobiological experiment carried out outdoors was affected by variable factors such as weather and temperatures. In the 1st run, strong UV radiation (~5.2 W m^{-2}) had a negative impact on the diatoms and silica uptake rates. The high temperature (highest average of 42.5 °C) also killed/bleached the diatoms in the 2nd run. In the 3rd attempt, three cycles of repeating silica uptake were successful under average temperature of 21 ± 5 °C and UV radiation of <0.2 W m^{-2}. NDMA and NMOR could be degraded simultaneously by the diatom-based photobiological treatment using sunlight as a light source.

Based on the experimental results, the highest silica uptake for OCWD GWRS and SAWS H2Oaks ROCs were 62 and 44 mg/L/day, respectively. With a desired treated silica concentration of 60 mg/L, a 20-million gallon (LWH: 1,330’ × 1,000’ × 2’) photobioreactor would be needed on the site of OCWD GWRS to treat its 17.6 MGD of ROC, while the reactor size would be 1.8 million gallons (LWH: 600’ × 200’ × 2’) for SAWS H2Oaks Center to treat its 1.11 MGD of ROC.

This research revealed the impacts of different factors on silica uptake rate using diatom-based photobiological treatment and treatability study of different ROCs. The results of the outdoor experiments verified many of my lab experimental results such as

the impacts of temperature, light intensity, as well as the non-requirement of continuous light, which will help our future research with larger scale continuous flow pilot photobioreactors.

I. INTRODUCTION

I.I. BACKGROUND

More than 70% of the earth is covered by water (El-Dessouky & Ettouney, 2002). However, only 2.5% of it is freshwater, which is vital as a drinking water resource, supporting humans' daily consumption, industrial and agriculture uses, and most lives on earth. Within the 2.5%, over 68 percent is stored in ice caps, glaciers, or icebergs, resulting in less than 1% of the global water resources is easily accessible freshwater such as surface water and shallow groundwater. The vast majority of water resources is seawater and brackish water, which have high salinity and cannot be used directly for human consumption.

According to the United Nations (UN) World Population Prospects 2019, the world's population reached 7.7 billion people in mid-2019. The Prospects also suggests that the population is expected to reach 8.5 billion in 2030 (United Nations, Department of Economic and Social Affairs, Population Division, 2019). Some areas have insufficient freshwater resources due to various reasons. For example, people are unable to get fresh water deep under the ground; freshwater resources such as lakes or rivers are overused, or traditional water storage like dams have limited capacities. Furthermore, more than 50% of world’s population has poor sanitation (UN Water, 2018). With all this, population growth combined with the city expanding and limited clean, safe water resources lead water scarcity an increasing concern worldwide.

Water scarcity highlighted the importance of alternative water management and augmentation strategies. Various technologies and methods were developed and implemented to increase accessible freshwater resources such as desalination, water reuse,

water conservation, stormwater management, and rainwater harvesting. The desalination technology, turning salty water into fresh water, have been developed and been used for years. Usually, seawater salinity ranges from 30,000 – 45,000 mg/L total dissolved solids (TDS) (Mickley, 2001), and brackish water contains TDS from 10,000 to 30,000 mg/L, while freshwater has less than 1,000 mg/L of TDS (Sandia, 2003). Desalination removes sodium, chloride, as well as other inorganic and organic components, from saline and brackish water. Thermal desalination and membrane desalination are the two main categories of desalination technologies. The thermal desalination is the process of turning salty water into vapor and condenses the vapor to produce fresh water while the membrane desalination utilizes membrane to separate permeate water and the concentrate. They are widely used all over the world to produce additional freshwater resources for human activities (Greenlee et al., 2009).

The reuse of treated wastewater has also emerged as an effective way to deal with water shortages. Water reuse can be an affordable and environmentally friendly option for augmenting water supplies and alleviating water scarcity (Kumar & Goyal, 2020). There are two general types of water reuse: non-potable reuse and potable reuse. For non-potable reuse, recycled water is used for non-drinking purposes, such as landscape and agricultural irrigation and industrial applications. For potable reuse, recycled water can be used as a potential drinking water source directly or indirectly. The difference between indirect and direct potable use is the presence and absence of environmental buffer, respectively. In most situations, the recycled water will be sent to an advanced water purification facility (AWPF) followed by a drinking water treatment plant for further treatment.

An increasing number of desalination plants and AWPFs were built in recent years to support sustainable water usage and increase water resources. One of the important and common technologies used in both plants/facilities is reverse osmosis (RO). RO is one of the methods available for membrane desalination. In the RO process, it applies pressure on the feed water to induce water permeation through a semipermeable membrane while rejecting salt. The great ability of removing monovalent ions, along with other organic and inorganic substances from feed water made RO the leading technology for desalination plants and AWPFs.

The RO process can produce 75% to 85% of freshwater from recycled water or brackish groundwater. The remainder of the 25% to 15% from the RO process is called concentrate or brine, which contains high concentrations of constituents and needs to be carefully managed and disposed of. Current brine management includes discharge to the ocean, sewer or surface water, deep well injection, evaporation ponds, and zero liquid discharge, which can be costly and might trigger potential environmental issues due to nutrients and trace organic compounds. As more inland brackish water desalination facilities (BWDFs) and AWPFs were built due to increasing freshwater demand, it will be more expensive to manage the concentrate. The ideal solution is to increase permeate water recovery during RO treatment, but it is restricted by the scaling of inorganic constituents such as silica and calcium on the RO membrane. Alternatively, the concentrate volume may be reduced through additional treatment to recover more water. Various treatment technologies such as bioreactor and advanced oxidation processes (Joo & Tansel, 2015) have been proposed to treat concentrate stream and increase water recovery.

In recent years, a diatom-based photobiological treatment for RO concentrate (ROC) has been developed that can be used in conjunction with secondary RO to enhance water recovery and increase water efficiency (Ikehata et al. 2017; 2018b). During the RO process, concentrated dissolved silica polymerize to form colloidal particles on the membrane, which will scale the membrane and then reduce permeate recovery. In this photobiological treatment, brackish diatoms, often found in rivers, lakes, and wetlands, have cell walls made by solid silica (SiO_2). By taking advantage of diatom's excellent ability to take up dissolved silica, nutrients, and other inorganic substances like calcium, secondary RO can be used to treat the photobiologically treated concentrate to produce an additional 10% to 20% freshwater, with as little as 5% final brine left. In this case, 95% or greater percentage of freshwater recovery can be achieved at the end as shown in Figure 1-1.

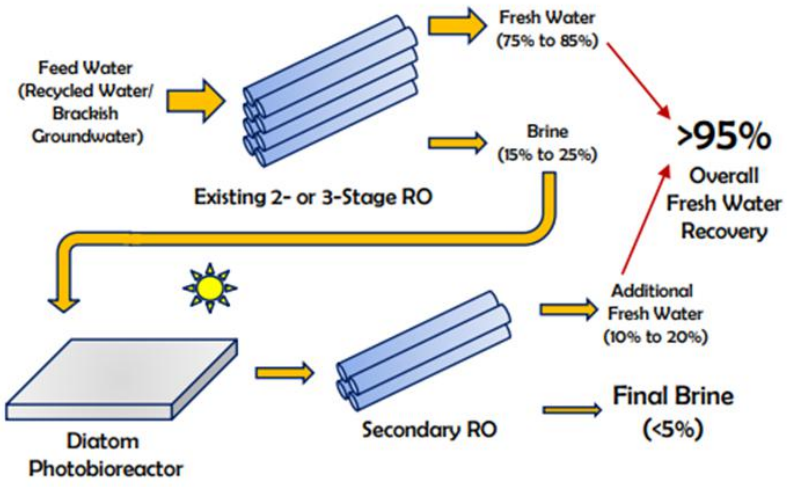


Figure 1-1. New RO Brine Treatment Technology Using Photobioreactor and Secondary RO (Ikehata, 2020).

Although the previous studies have shown a strong potential of the diatom-based photobiological process, several technical challenges have been identified (Ikehata & Kulkarni, 2018), including:

- Continuous flow operation of the photobioreactor and secondary RO unit
- Optimization and acceleration of silica and other constituent uptake and/or removal
- Contamination control in the photobioreactors, and
- Biomass characterization and harvesting

I.II. OBJECTIVES

The main objective of this study is to optimize and accelerate the silica uptake using brackish water diatom *Gedaniella flavovirens* Psetr3 to reduce the volume of photobioreactor and capital cost. By utilizing the following equations:

For 0^{th} order kinetics,

$$t_0 = (C_0 - C_t)/k \quad [1]$$

$$V = Qt_0 \quad [2]$$

where t_0: time (in days) needed to reach desirable silica uptake, C_0: initial mass concentration (in mg/L), C_t: mass concentration at time t_0 (in mg/L), k: silica uptake rate (in mg/L/day), V: volume of photobioreactor (in gallons), Q: volumetric flow rate (in gallons per day).

For constant mass concentration reduction under steady state conditions, higher silica uptake rate indicates shorter time needed to complete the treatment. With constant volumetric flow rate, shorter time indicates a smaller tank/pond to be built and a lower capital cost. Therefore, optimization of silica uptake rate is directly related to reduction in capital cost, and higher treatment efficiency.

To achieve the goal, specific objectives are established in my thesis research. The subgoals include:

- Confirm the requirements for the repeatable photobiological treatment;
- Supplementary nutrients determination;
- Investigate impacts of different factors on silica uptake rate, such as incubation temperatures, as well as light colors, intensities, illumination duration and temperatures;
- Find the optimum conditions for accelerating the silica uptake;
- Treatability study of six ROCs by the photobiological treatment;
- Check the applicability of using outdoor sunlight as the light source;
- Investigate the removal of N-nitrosamines, including *N*-nitrosodimethylamine (NDMA) and *N*-nitrosomorpholine (NMOR); and
- Determine the approximate size of full-scale photobioreactor for a AWPF and a BWDF.

II. LITERATURE REVIEW

II.I. DESALINATION AND ADVANCED WATER PURIFICATION USING REVERSE OSMOSIS

More than 70% of the earth is covered by water, with 96.5 % of the water located in oceans and seas (Gleick, 1996). Due to the high salinity of sea water, it cannot be used directly as drinking water resource which is vital for human consumption. Besides seawater, brackish water (surface water such as estuaries and groundwater) is less salty but still above the maximum standard of freshwater. Freshwater is essential to agricultures and industries development, as well as ecological balance. To support daily consumption and sustain limited freshwater resource for future generations, various solutions were developed and applied. The concept of saltwater desalination emerged to produce additional fresh water, which became an important source of drinking water production.

Desalination is the process of removing salts and mineral components from brackish and saline water. The concentration of TDS is often used to define the water resource. Seawater salinity ranges from 30,000 to 45,000 mg/L TDS (Mickley, 2001) and brackish water contains about 1,000 to 30,000 mg/L TDS, while freshwater has less than 1,000 mg/L of TDS (Sandia, 2003). Many countries have drinking water standards for TDS level. The standard limit might varies depend on individual states and regions. The United States Environmental Protection Agency (U.S. EPA) has secondary (non-enforceable) standards of 500 mg/L TDS (U.S. EPA, 2002). California has recommended secondary maximum contaminant level (MCL) of 500 mg/L TDS, and upper limit of 1,000 mg/L (California Code of Regulations, 2007). Florida has a standard of 500 mg/L

TDS (Florida Administrative Code, 2007). Texas has a secondary standard of 1,000 mg/L TDS (Texas Administrative Code, 2000). Most desalination plants are designed to achieve 500 mg/L of TDS or less (Gaid & Treal, 2007; Petry et al., 2007; Sanz et al., 2007; Xu et al., 2007).

There are two main categories in desalination technologies: thermal desalination and membrane desalination. Thermal desalination or distillation is the process of turning salt water into vapor and condenses to produce fresh water, which has been used for hundreds of years. Middle Eastern countries pioneered implementation of seawater thermal desalination with multi-effect distillation, which uses a steam heat source and a series of evaporators (Bragg-Sitton, 2015), and later using multi-stage flash distillation (Van der Bruggen & Vandecasteele, 2002), a process which feed seawater is pumped to higher pressure and heated to near boiling in multiple stages, then generate vapor is condensed by incoming seawater (Bragg-Sitton, 2015). Thermal desalination is quite energy consuming, but good for feed water contains extremely high salinity, and high fouling potential which may foul membranes in the membrane desalination process.

Membrane desalination has been rapidly developed since 1960s (Loeb & Sourirajan, 1963). Electrodialysis (ED)/electrodialysis reversal (EDR), nanofiltration (NF) and RO are the three main processes in membrane desalination facilities. The ED/EDR process will separate salt through ion exchange membrane with electric current. The NF process uses nanometer-sized pore membrane to filter out substances larger than 1 to 10 nm in size. Also, NF membrane can be used to remove some multivalent ions such as calcium and magnesium that contribute to water hardness. (Choi et al., 2001; Gorenflo et al., 2002). During the RO process, it applies pressure on the feed water to induce water

permeation through a semipermeable membrane while rejecting salt. Comparing to ED/EDR and NF, RO can remove most monovalent ions such as sodium and chloride, along with other organic and inorganic substances. The great ability of removing both organic and inorganic substances from feed water made RO the leading technology of choice for desalination plants.

Furthermore, the RO process is commonly implemented in AWPFs, which is related to the water reuse field. Water reuse as an alternative strategy to augment water resources has been widely used across the U.S. There are two general types of water reuse: non-potable reuse and potable reuse. For non-potable reuse, recycled water is used for non-drinking purposes, such as agricultural irrigation and industrial applications. For potable reuse, recycled water can be used as a potential drinking water resource directly or indirectly (Kumar & Goyal, 2020). Indirect potable reuse (IPR) implies that recycled water is returned to the environment such as rivers, lakes, or groundwater aquifers before being sourced for drinking water supply. Direct potable reuse (DPR) involves the direct delivery of treated recycled water from wastewater treatment plants or AWPFs to drinking water plants or distribution systems (Cotruvo & Bell, 2014). The *de facto* reuse is considered as one of the IPR, which involves the discharge of treated wastewater from an upstream community as the source water of drinking water treatment plant intake downstream (Gerrity et al., 2013). As the IPR and DPR are quickly becoming viable options for alleviating water shortage problems in many areas, more AWPFs and drinking water treatment plants will be established to serve the purpose of potable reuse.

It is important to have wastewater treatment especially when to increase immediate water resource reuse in response to increasing water scarcity issues with a

technologically driven water cycle that is faster than the environmental buffer (Capodaglio, 2020). According to the global wastewater reuse type after advanced water treatment, shown in Figure 2-1, majority of the water are reused in agriculture, landscape and industrial, which also implies that the treatment standards are less restrictive than those for drinking water (WHO/UNEP, 2006). As industrial water consumption accounts for around 20% of global wastewater reuse, the percentage is estimated to increase in the near future. The largest wastewater reuse in the U.S. is industrial cooling such as power plants, or high-technology manufacturing (USEPA, 2012). In worldwide, most reuse consumption and application are related to irrigation, which includes agricultural and landscaping. An estimation indicates that around 12% of freshwater withdrawn for irrigation can be replaced by treated wastewater (UN-WATER, 2018b). The reason is that reclaimed water is a good source of nutrients, which serves the purposes of irrigation very well. The excessive nutrients can be used to promote root systems and plant growth (Capodaglio, 2020). The undiscriminating selection of high treatment levels from regulations may increase wastewater treatment costs and so discourage water reuse (Jiménez & Asano, 2008).

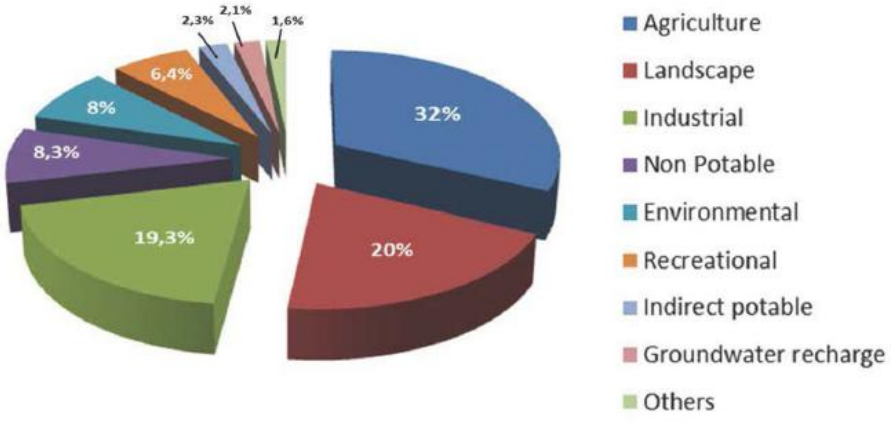


Figure 2-1. Global wastewater reuse type after advanced water treatment (data from UNWATER, 2017).

The challenges that water reuse applications are facing include public acceptance and perception, treated water quality monitoring, health consideration, and government regulatory. Public acceptance and perception as a major obstacle for wastewater reuse often related to public education levels. It was shown that indirect potable reuse is often overlooked, and poorly treated water are discharged into the upstream of a drinking water treatment plant. And according to a study in three US cities, about 96% of respondents ignored its presence (Capodaglio, 2020). Therefore, the wide applications of wastewater reuse must be supported by consistent regulatory framework (Harris-Lovett et al., 2015).

NDMA as a probable human carcinogen (USEPA, 1993) can permeate through RO membranes (Fujioka et al,. 2016), which often detected higher than California regulatory notification level (NL) of 10 ng/L (CDPH, 2015) in RO permeate (Plumlee et al., 2008; Poussade et al., 2009; Farré et al., 2011; Fujioka et al., 2013b). Furthermore, as a disinfection byproduct which mostly formed with the use of ozone and chloramines, NDMA emerged as a growing concern in potable water reuse (Mitch et al,. 2004; Sgroi et al,. 2018; Kadmi et al,. 2014; Kodamatani et al,. 2018).

Wastewater reuse has existed for a long time which severs various uses. With different purposes, diverse technologies are selected to satisfy the quality and quantity of the water demands. Unlike the natural water cycling which uses environmental buffers, shorter reuse cycle requires more intense technological interventions (Capodaglio, 2020). Nowadays, there are various treatment processes that are technologically feasible to be customized to achieve desirable water quality standards such as membrane filtration, bioelectrochemical systems, advanced oxidation processes and so on. RO as one of the membrane filtrations are widely used nowadays.

New RO installations were steadily increasing. According to the American Membrane Technology Association, there were more than 770 municipal brackish water RO plants in the U.S. (Ikehata & Kulkarni, 2018) and over 1,200 full-scale RO facilities in the United States as of April 2020 (AMTA, 2020). Table 2-1 shows the different types of feed water and their characteristics for RO.

Table 2-1. Different types of RO feed water

RO feed water	Characteristics
Seawater	Coastal areas, high salinity & TDS, lower permeate flux due to high osmotic pressure
Brackish groundwater	Lower TDS than seawater, aquifers, higher permeate flux
Brackish surface water	Estuaries, brackish lakes, marshes, higher permeate flux
Reclaimed water	Treated wastewater from variety of sources

II.II. MAJOR ROCS INTRODUCTION

Two of the ROCs from Orange County Water District Groundwater Replenishment System (OCWD GWRS) and San Antonio Water System (SAWS) H2Oaks center were widely used in my research. In order to meet the water demands from around 2.3 million residents, the Orange County Water District draws water from a groundwater basin which related to Santa Ana River, Colorado River and Northern California (Guendert, 2004). Due to a local drought, groundwater over-abstraction, and increasing projected population, the Groundwater Replenishment System was implemented to meet the future drinking water needs. The OCWD GWRS is a IPR water purification facility located in Fountain Valley, CA. Its advanced treatment process combines microfiltration (Figure 2-2), RO (Figure 2-3), and ultraviolet light with hydrogen peroxide can treat secondary wastewater to the quality that equivalent or better

than drinking water (Guendert, 2004). The OCWD GWRS currently has a water production capacity of 100 million gallons per day (MGD), and around 35 MGD are injected into wells to serve as a seawater intrusion barrier, while the remaining 65 MGD are sent to the recharge basin which serves as a natural filter for deep aquifer replenishment (Orange County Water District, 2021). Currently, The OCWD GWRS produces around 17.6 MGD of RO concentrate.

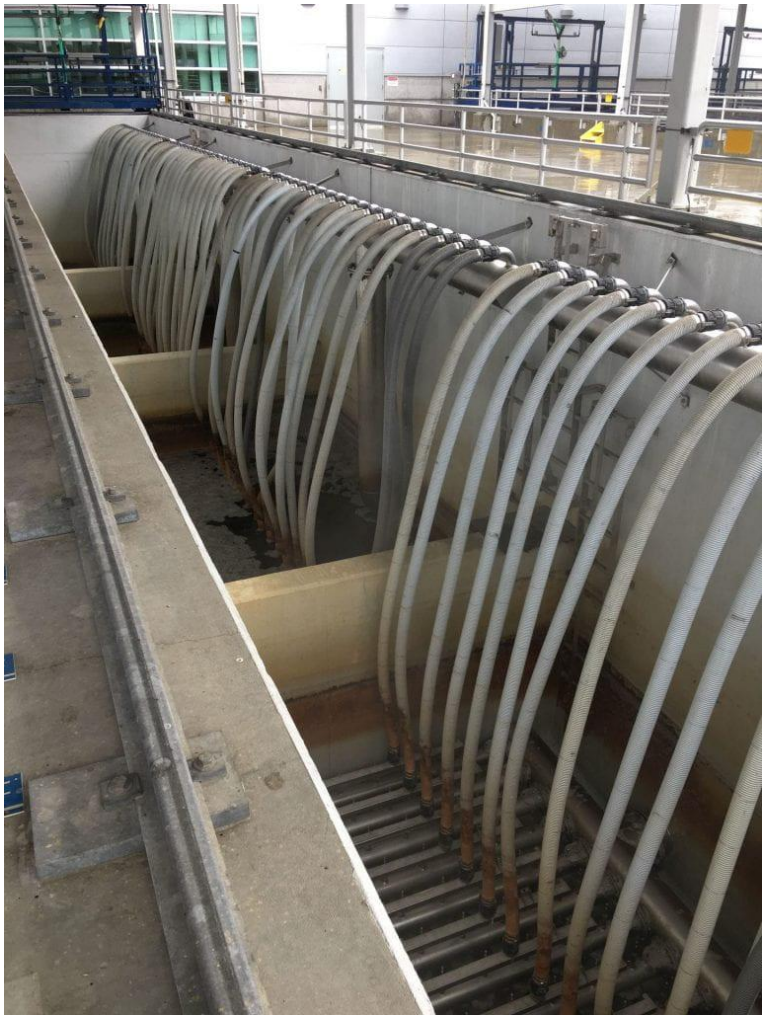


Figure 2-2. Microfiltration in OCWD GWRS (Photo courtesy of Dr. Keisuke Ikehata)

Figure 2-3. RO in OCWD GWRS (Photo courtesy of Dr. Keisuke Ikehata)

The SAWS H2Oaks Center (Figure 2-4) is located in south Bexar County, Texas. The Brackish Groundwater Desalination Plant here pumps brackish groundwater from Wilcox Aquifer and treated it with three-stage RO and produces approximately 12 million gallons of drinking water per day. After the treatment, the RO concentrate is injected though wells into the injection zone that is more than one mile deep under the ground (San Antonio Water System, 2021). The SAWS H2Oaks center produces 1.11 MGD of RO concentrate daily.

Figure 2-4. The SAWS H2Oaks Center in San Antonio, Texas

Figure 2-5. The RO system inside SAWS H2Oaks Center in San Antonio, Texas

II.III. ROC MANAGEMENT

The waste stream produced after RO is called RO concentrate or brine. The high recovery rates of RO system concentrate the soluble salts in feed water and increases the chances of precipitation and deposition on the RO membrane, which lead to efficiency reduction and other problems (Jawor & Hoek, 2009). This is known as scaling, which occurs when the solubility limits of dissolved salts are exceeded under pressures during pure water extraction (Tran et al., 2007). Common scalants such as calcium carbonate ($CaCO_3$), calcium sulfate ($CaSO_4$), barium sulfate ($BaSO_4$) and silica (SiO_2) often forming crystals that precipitate on the membrane surface or in the bulk concentrate (Zhao et al., 2012). When the precipitated solids accumulate on the membrane surface, it may result in permeate flux decline and increase in applying pressure on the feed water, which shorten the service life and increases the maintenance cost (Amiri & Samiei, 2007). In addition to inorganic scaling, other major types of fouling include organic, colloidal and biofouling. Organic fouling formed when different types of organic macromolecules such as proteins deposit on the membrane surface; Colloidal fouling usually form from the accumulation of particles which sizes between dissolved and suspended solids like iron oxides, aluminum and manganese; Biofouling is the attachment of microorganisms on the membrane surface which accumulates and form biofilm (Matin et al., 2019).

Due to the high concentrations of dissolved solids and other contaminants, the ROC needs to be carefully managed and disposal of. For seawater RO plants, concentrate is often discharged back to the ocean. The major concerns are the pumping system and length of pipes connect the plants and undersea (Mooij, 2007; Ravizky & Nadav, 2007). For brackish water and recycled water RO plants, discharge to ocean is limited to costal

facilities, and not always applicable and cost-efficient for inland plants due to the long piping needed to transport concentrate. Discharging to rivers or lakes may change the salinity of receiving water, that may have negative influences on aquatic lives in that water system and may trigger some other environmental problems (Mickley, 2004). Other disposal methods include sewer discharge, evaporation ponds, deep well injection, and zero liquid discharge. Table 2-2 shown below lists the benefits and deterrents of each method.

Table 2-2. Comparison of different ROCs management methods. (Mickley, 2001, 2004; Nicot et al., 2007)

Methods	Benefits	Deterrents
Ocean and surface water discharge	• Relatively low cost • Large discharge volume	• Potential environmental problems • Limited for inland facilities
Sewer discharge	• Low cost • Large discharge volume	• Need to pay surcharge • Discharge restricted if the concentrate flow is too large or too saline • Possible increasing pipes corrosion
Evaporation ponds	• Utilize solar energy • Inexpensive	• Salts and chemicals might leach into the soil or groundwater • No suitable climate or unavailable land to build ponds in some areas
Deep well injection	• Economical • Can handle large volumes	• Corrosion and leakage of wells • Possible seismic activities • Unknown well lifetime
Zero liquid discharge	• Minimal waste production • Combine with other methods to achieve higher water recovery • Reducing membrane scaling	• High capital cost • High energy requirement

II.IV. PHOTOBIOLOGICAL TREATMENT OF ROC

Recently, there are increasing research that utilizing algae-based photobiological treatment for ROCs. A diatom-based photobiological treatment was developed for silica (SiO_2) and hardness removal that precipitate and cause scaling on RO membrane during high pressure process which is a difficulty that many desalination plants and AWPFs are facing. A mixture of brackish diatoms obtained from the agricultural drainage water, and later identified, isolated were used in the treatment. With a ROC from advanced water

reclamation plant, more than 75% of silica and 90% of orthophosphate were removed in 5 days. Additional RO scaling causing inorganic cations, including calcium (49%), iron (>96%), and manganese (81%) were effectively removed by the photobiological process (Ikehata et al., 2017). Later, further research and experiments were conducted with two strains of brackish diatoms: *G. flavovirens* (used to be called *Pseudostaurosira trainorii*) and *Nitzschia,* along with two ROCs from full-scale AWPFs and one ROC from brackish groundwater RO plant. Additional nutrients were needed for brackish groundwater RO concentrate due to insufficient phosphorus to complete silica removal. Otherwise, this photobiological treatment showed a great potential as a pretreatment of RO concentrate due to efficient removal of silica, orthophosphate, calcium, iron, manganese, bicarbonate, ammonia, and nitrate (Ikehata et al., 2018a).

A photobiological treatment followed with secondary RO was conducted to explore the chance of enhancing water recovery, along with removal of important trace wastewater contaminants, such as pharmaceuticals and personal care products (PPCPs), as well as metals and NDMA. Also, a pilot-scale experiment was designed, constructed, and conducted. The results showed that the photobiological treatment combined with secondary RO achieved additional 10 % water recovery. With 85 % from the primary RO unit, it represents 95% recovery overall. Furthermore, the photobiological treatment removed 12 pharmaceuticals and personal care products, as well as NDMA primarily via photolysis with UV radiation (Ikehata et al., 2018b). In a later study, 11 RO concentrates from six full scale potable reuse facilities were tested the treatability of the diatom based photobiological treatment. Eight of the RO concentrates were successful treated while the ammonia-N concentration in the other three samples were too high for completing the

treatment (Ikehata et al., 2019).

To further test the treatability of photobiological treatment with different RO concentrates, 11 RO concentrate samples from six full-scale potable reuse facilities were treated with brackish diatoms at a laboratory scale. 8 out of 11 samples were tested successfully while the other three samples had a concentration of ammonia (as low as 16 $mg \cdot L^{-1}$) that was unsuitable for treatment due to ammonia toxicity. More research would be needed for understand the impact of RO concentrate water quality and optimize the growth of diatoms and reactive silica uptake under different treatment conditions (Ikehata et al., 2019). The factors influencing reactive silica uptake from a brackish groundwater RO concentrate was discussed. A supplementary of 4 mg/L orthophosphate dose (1.28 mg/L as P) and nitrate dose of 12 mg/L as N were found to be adequate for the growth of the diatom to complete the treatment. Furthermore, the study found that vigorous mixing negatively affected the reactive silica uptake rate. Additional carbon dioxide reduced calcium removal efficiency due to decreased pH, which was not recommended since calcium is one of the major scalants. Also, direct exposure to sunlight leads slower silica uptake rate compared to LED light. More studies should be conducted to investigate factors affecting silica uptake by diatoms, and thus achieve advanced water recovery with low capital cost (Kulkarni et al., 2019).

Two green algae: *Chlorella* and *Scenedesmus* were used as a novel biological approach to removal nitrogen, phosphorus, and calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions simultaneously from the ROC of wastewater reclamation plants. Both two strains successfully worked well in ROC, which achieved 89.8% and 92.7% of nitrogen and phosphorus removal, respectively. The two strains could also remove 55.9% - 83.7%

Ca^{2+} and up to 56.0 % of Mg^{2+} from the sample (Wang et al., 2016). A microalga, *Scenedesmus quadricauda* was found that able to induce the degradation of refractory organics consisting of humic-like and polysaccharide-like substances in synthetic RO concentrate. It is an inexpensive strategy to degrade refractory organics comparing to electrochemical oxidation technologies due to alga's abilities of self-repair reproduction and nutrient uptake (Maeng et al., 2018). Later, the same alga was used to investigate the treatment on the growth of *Escherichia coli* and removal of trace organic compounds from the RO concentrate. With CO_2 supplementation, it removed color-causing refractory organic matter along with inorganic nutrients and resulted in a considerable inhibition of *E. coli* growth from synthetic RO concentrate. However, further work is needed and investigated with real RO concentrates (Maeng et al., 2018). In another research, algal treatment was also combined with ozone pretreatment for synthetic ROC prior to microfiltration. The objective of this research mainly focuses on the minimizing the fouling of polyvinylidene-fluoride on membranes and enhancing the restoration of membrane permeability. The study showed markedly improved performance was achieved when ozonation was combined with algal treatment, which also showed as a great technology to minimize trace organic compounds levels such as caffeine and carbamazepine (Woo et al., 2019)

II.V. DIATOMS

The first certain record of a diatom was published by an English country man back in 1703. It was a remarkable judgement to put diatom into plant category considering that all he had for comparison were vascular plants, seaweeds, and bryophytes. In the late 18^{th} century, various diatoms were described and given Latin

binomials. However, the debate of diatom nature has been discussed in half-way through 19th century. Diatoms were classified as animal by authors such as Bory, Ehrenberg due to the motile, unicellular forms and protoplast, with plastids and granules considered as digestive system of animals. In contrary, naturalists considered diatom as plants based on the macroscopic growth of tube-dwelling diatoms, as well as various colonial forms with sedentary habit. In 1844, Kützing's monograph treated all diatoms as plants, and classified them as algae which won agreement for most people. (Round et al., 1990)

Diatoms play an important role in natural systems. Diatoms in oceans and freshwater are valuable indicators of past environment. There were increasing diatom studies as limnology science going, and scientist believed that diatom growth would impact the biological, chemical, and physical process of inland freshwaters. Back in 1980's, diatoms could be used to detect pH changes that related to acid rain. By taking advantage of diatom's nature of siliceous cell wall, it could also be used in economic ways such as industries application (Round et al., 1990).

There are more than 1,000 species of oceanic diatoms, and more than four times the number habitat shallow marine, brackish, and fresh waters (Harper & Knoll, 1975). Diatoms is a major component of phytoplankton community as the predominant siliceous organisms in marine environment (Martin-Jézéquel et al., 2000). Diatoms are unicellular, eukaryotic microorganisms, which contains the same protoplast as other eukaryotic algae. However, the distinctive characteristic is that the cell wall is highly impregnated with silica (SiO_2), forming a structure called frustule. (Round et al., 1990, Martin-Jézéquel et al., 2000). In 1965, Lund found that 60% of the dry weight of *Aulacoseira italica* subsp. *subaractica* cell is made of silica (Round et al., 1990). Based on research, silicon is a

major limiting nutrient that controls diatom growth and productivity. Furthermore, the cellular energy for silicification is more directly involved with aerobic respiration instead of photosynthetic metabolism (Martin-Jézéquel et al., 2000). Figure 2-6 below shows the exploded view of the diatom frustule, which composed of the epivalve (E), hypovalve (H), epicingulum (EC) and hypocingulum (HC) (Round et al., 1990).

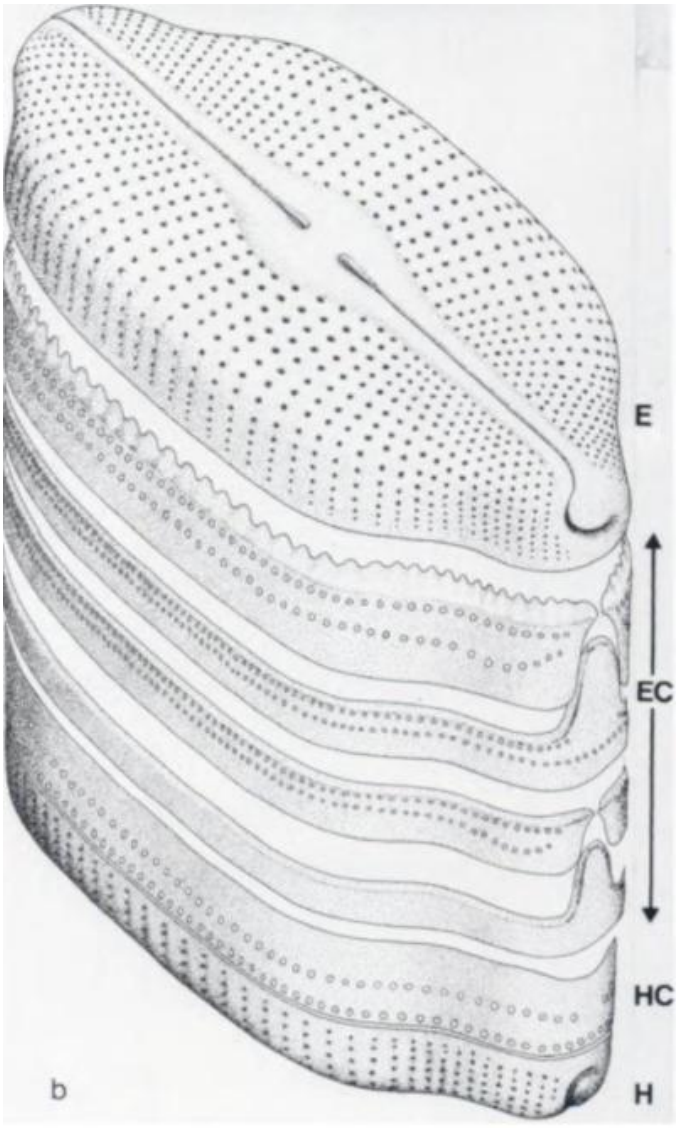


Figure 2-6. The structural view of the frustule of a naviculoid diatom (Round et al., 1990)

III. MATERIALS AND METHODS

III.I. MATERIALS

III.I. I. DIATOMS

A unialgal culture of brackish diatom: *G. flavovirens* Psetr3 (Figure 3-1) was provided by Dr. Shinya Sato, Fukui Prefectural University (Obama, Japan). The primary cultures were incubated under continuous illumination for more than two weeks, then were transferred to three 15-mL sterile VWR SuperClear™ polypropylene centrifuge tubes (VWR International, Radnor, PA). After several weeks of incubation, the amount of biomass was decent enough to create seed cultures. Then around 1 mL of biomass mixed solution was transferred to each larger 50-mL VWR culture tubes with filter-sterilized wastewater ROC from OCWD GWRS (Fountain Valley, CA) and maintained until use.

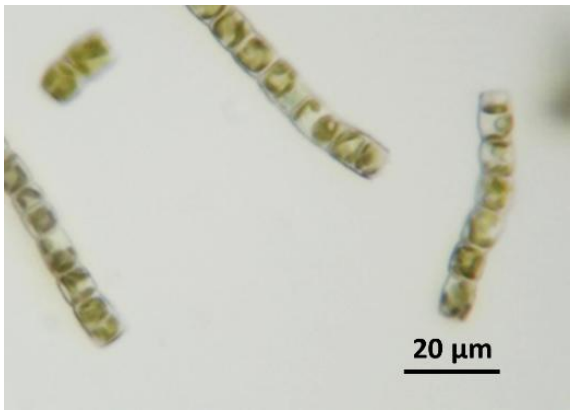


Figure 3-1. Photomicrograph of *G. flavovirens* Psetr3

Acrodisc 32 mm syringe filters with 0.8/0.2 µm hydrophilic polyethersulfone membrane (Pall Newquay, Cornwall, UK) were used to filter ROCs. After confirming the biomass' active growth, ROC was replaced every week to ensure decent amount of

biomass for photobiological experiments. Subcultures were created by transferring 0.5 or 1.0 mL of biomass suspension using sterile pipet tips to new culture tubes containing filter sterilized OCWD ROC and replaced every week to ensure sufficient nutrients supply.

III.I. II. CHEMICALS

Sodium phosphate dibasic anhydrous (Na_2HPO_4) (VWR; Solon, OH) was used to prepare 1 g/L orthophosphate stock solution. By calculating the mass balance equation, 0.14948 grams of Na_2HPO_4 powder was weighted and transferred into 100 mL volumetric flask with distilled water and mixed well. After the powder was all dissolved, filter sterilized the stock solution using 0.8/0.2-μm sterile syringe filters into two sterile 50-mL centrifuge tubes with proper label and stored in the fridge. F/2 medium concentrate (Part B; Fritz Aquatics, Mesquite, TX) containing 6% nitrogen (N) and 2% phosphate (P_2O_5) was used as a nutrient source. A 2.7% F/2 part B solution containing 1.0 g/L of orthophosphate and 3 g/L of nitrate-N was prepared by adding 2.7 mL of algae food solution to a 100-mL volumetric flask and diluted with ultrapure water. Then, the solution was filtered and stored in the fridge. The GenPure Pro system (Thermo Scientific Barnstead, Sweden) was used to supply ultra-purified distilled water for research use. The 100 μg/L NDMA standard solution was obtained from Supelco, St. Louis, MO.

III.I. III. ROC SAMPLES

The ROC samples obtained from OCWD GWRS in Fountain Valley, CA and SAWS H_2Oaks center in San Antonio, TX were used as model of AWPF and BWDF ROCs, respectively, in all the comparison experiments. Additional ROC samples were collected at four different facilities, including Hamby Water Reclamation Facility (WRF,

Abilene, TX), Kay Bailey Hutchison Desalination Plant (KBHDP, El Paso, TX), a closed-circuit RO pilot (CCRO) at OCWD, and Edward C. Little Water Recycling Facility (ECLWRF, El Segundo, CA), as shown in Table 3-1 and tested in the treatability experiments.

Table 3-1. Six RO concentrate samples from different water treatment facilities.

Name	Type	State	City	Sample Collected Date
OCWD GWRS	AWPF	CA	Fountain Valley	September 23, 2019/September 11, 2020/March 25, 2021
SAWS H2Oaks	BWDF	TX	San Antonio	August 22, 2019/March 23, 2020 /October 15, 2020
Abilene Hamby WRF	AWPF	TX	Abilene	February 12, 2020
El Paso KBHDP	BWDF	TX	El Paso	October 30, 2019/September 15, 2020
OCWD CCRO	AWPF	CA	Fountain Valley	December 6, 2019
WBMWD ECLWRF	AWPF	CA	El Segundo	November 27, 2019

Abbreviations: AWPF: advanced water purification facility, BWDF: brackish water desalination facility, CCRO: closed-circuit RO, WBMWD: West Basin Municipal Water District, ECLWRF: Edward C. Little Water Recycling Facility, WRF: water reclamation facility, KBHDP: Kay Bailey Hutchison Desalination Plant

III.II. EQUIPMENT

III.II. I. ANALYTICAL

The concentrations of water quality parameters were tested by Hach DR1900 spectrophotometers (Loveland, CO) with corresponding Hach methods (see Table 3-3 in III.III. I Water Quality Analysis). A Hach 2100Q turbidimeter were used to test turbidity. *In vivo* chlorophyll and phycocyanin were determined by an AquaFlour fluorometer (Turner Designs; San Jose, CA). Conductivity and pH were tested by Hach Pocket Pro Testers. A Hach DRB 200 was used for total and dissolved chemical oxygen demand.

UV_{254} was measured with an Evolution 201 UV-Visible Spectrophotometer from Thermal Fisher Scientific (Waltham, MA). Photosynthetically active radiation (PAR), ultraviolet light (UV) radiation, and light spectrums were measured with a MQ-500 full-spectrum quantum meter, an MU-200 UV sensor (spectral range: 250 to 400 nm), and a SS-110 Spectroradiometer (spectral range: 340 to 820 nm) (Apogee Instruments, Logan, UT). Hach Digital Titrators were used for measuring total and calcium hardness, alkalinity, and chloride. An AmScope 40X-2000X Trinocular Compound Darkfield Microscope was used to take photomicrography of diatoms. A digital timer (125 VAC, 60Hz, GE; China) was used to control the light duration in the experiment.

III.II. II. PHOTOBIOLOGICAL WATER TREATMENT

Several plastic 5-gallon buckets [Lowe's, Dimensions: 14.25 inches (height), 12.5 inches (diameter)] with a reflective bubble wrap roll (ULINE, Product # S-11476) were used as incubators for the photobiological treatment experiments. The reflecting bubble wrap was used to cover the bottom and inside wall of the buckets (Figure 3-2 and 3-3).

Figure 3-2. Incubator

Figure 3-3. Incubator (inside)

Refrigerated and non-refrigerated incubators from Thermo Fisher Scientific (Waltham, MA) were also used for temperature control.

Figure 3-4. Refrigerated incubators

Figure 3-5. Non-refrigerated incubators

Reactors used include sterile 50-mL polypropylene centrifuge tubes, 100-mL polystyrene coliform bottles, and 500-mL polycarbonate jars. Temperature USB data loggers (Lascar Electronics, Erie, PA) were used to continuously measure the temperature in the incubators. Clip lamps and LED bulbs (2,700, 3,000, 4,000, and 5,000 K) were used as a light source. Colored LED bulbs listed in Table 3-2 and shown in Figure 3-6 were also tested.

Table 3-2. LED bulbs and products #

Bulb	Manufacturer	Product Model #
2700 K, 800 Lm, 10 W	GE	LED10DA19/827
3000 K, 800 Lm, 10 W		LED10DA19/830
4000 K, 800 Lm, 10 W		LED10DA19/840 120
5000 K, 800 Lm, 10 W		LED10DA19/850
3000 K, 60 Lm, 8 W, Green	Philips	929001997905
3000 K, 60 Lm, 8 W, Red		929001997805
3000 K, 60 Lm, 8 W, Blue		929001998005
3000 K, 60 Lm, 8 W, Yellow		929001998105
Soft White, 15W	Great Value	567881226

Figure 3-6. Philips colored bulbs

III.III. METHODS

III.III. I. WATER QUALITY ANALYSIS

Table 3-3 summarizes the analytical methods for water quality parameters used in this study. Table 3-5 shows the water quality of the ROC samples listed in Table 3-1. The NDMA concentrations were tested with high-performance liquid chromatography

followed by photochemical reaction and chemiluminescence (HPLC-PR-CL) (Kodamatani et al., 2018), which has a detection limit of 0.09 ng/L, 0.25 ng/L, 0.47 ng/L, 0.42 ng/L for NDMA, NMOR, NMEA, and NPYR, respectively.

Table 3-3. Water quality parameters and corresponding analytical methods

Parameters	Method	Method #
Reactive silica	Silicomolybdate Method	Hach 8185
Orthophosphate	USEPA PhosVer 3® (Ascorbic Acid) Method	Hach 8048
Ammonia-N (HR)	Salicylate Method	Hach 10031
Nitrate-N (LR)	Dimethylphenol Method	Hach 10206
Iron	USEPA FerroVer® Method	Hach 8008
Copper	USEPA Bicinchoninate Method	Hach 8506
Manganese (LR)	1-(2-Pyridylazo)-2-Naphthol PAN Method	Hach 8149
Calcium hardness	Titration Method with EDTA	Hach 8204
Chlorine, Free	USEPA DPD Method	Hach 8021
Chlorine, Total	USEPA DPD Method	Hach 8167
Sulfate	USEPA SulfaVer 4 Method	Hach 8051
Color at 455 nm	Platinum-Cobalt Standard Method	Hach 8025
Potassium	Tetraphenylborate Method	Hach 8049
Chloride	Silver Nitrate Method	Hach 8207
Alkalinity	Phenolphthalein and Total Alkalinity	Hach 8203
Total hardness	Titration Method with EDTA	Hach 8213

III.III. II. PHOTOBIOLOGICAL TREATMENT EXPERIMENT

Series of bench-scale experiments were conducted to investigate the factors affecting the silica uptake by *G. flavovirens* Psetr3 in OCWD GWRS and SAWS H2Oaks ROCs. The preliminary experiments were conducted first to confirm the experimental settings and requirements for completing the bench-scale experiments and to define silica uptake rate in my research. The factors impact experiments were comparing the differences between light temperatures (2,700, 3,000, 4,000, and 5,000 K), light colors (white, yellow, green, blue, and red), intermittent (12 hours on and 12 hours off) and continuous light, incubation temperature (10, 20, 30, and 40 °C), and light intensity (50,

100, 200, 310, and 510 μmol m^{-2} s^{-1}). Furthermore, the treatability of the photobiological treatment for four more ROCs from different AWPFs and BWDFs were investigated. At the end, outdoor experiment was also conducted to look into the treatability of sunlight in Texas and removal of NDMA. Table 3-4 shows a list of conducted experiments and corresponding objectives. And Table 3-5 shows the water quality parameters of the six ROCs in my experiment.

Table 3-4. Planned experiments and corresponding objectives

Type	Experiments	Objectives
Preliminary	Comparison of light and dark conditions in the photobiological treatment of OCWD GWRS ROC	To confirm the requirement of light for silica uptake by diatoms
	Comparison of OCWD GWRS and SAWS H2Oaks ROCs	To test the treatability of two model ROCs that represent AWPFs and BWDFs and understand the difference between the two ROCs
	Orthophosphate optimization with SAWS H2Oaks ROC	To determine the optimum orthophosphate concentration to complete the photobiological treatment
Factors	Comparison of LEDs with different light temperatures (2700, 3000, 4000, 5000 K) with OCWD GWRS ROC and SAWS H2Oaks ROC	To determine the optimum light temperature for the photobiological treatment
	Comparison of PAR [50, 100, 200, 310, and 510 µmol/(m^2s^1)] with OCWD GWRS ROC and SAWS H2Oaks ROC	To determine the optimum PAR for the photobiological treatment
	Comparison of light colors (green, red, blue, yellow, and white) with OCWD GWRS ROC and SAWS H2Oaks ROC	To determine the optimum light color for the photobiological treatment between these two ROCs
	Comparison of intermittent and continuous light with OCWD GWRS ROC and SAWS H2Oaks ROC	To test the impact of intermittent and continuous light on the photobiological treatment between these two ROCs
	Comparison of incubation temperatures (10, 23, 30, and 40 °C) with OCWD GWRS ROC and SAWS H2Oaks ROC	To determine the optimum incubation temperature for the photobiological treatment between these two ROCs
Treatability	Comparison of Abilene Hamby WRF & El Paso KBHDP ROCs, and OCWD CCRO & WBMWD ECLWRF ROCs	To test the treatability and understand the difference among these ROCs
Outdoor/ NDMA	Investigation of the removal of *N*-nitrosamines (such as NDMA) by the photobiological treatment	To investigate the removal of *N*-nitrosamines from OCWD ROC by the photobiological treatment under different conditions

Table 3-5. Water quality data for six RO concentrate samples

Parameters	OCWD GWRS	SAWS H2Oaks	Abilene Hamby WRF	El Paso KBHDP	OCWD CCRO	WBMWD ECLWRF
Calcium (mg/L)	779	260	529	873	950	367
Magnesium (mg/L)	140	400	1,010	290	927	493
Iron (mg/L)	0.3	0.33	0.14	0.08	<0.02	0.27
Ammonia-N (mg/L)	6	5	3.7	N/A	0.46	152
Chloride (mg/L)	1,670	2,370	1,640	7,000	3,440	1,240
Sulfate (mg/L)	1,000	4,500	1,280	1,360	2,100	1,300
Bicarbonate (mg/L)	590	605	507	244	1,120	631
Nitrate-N (mg/L)	60	0	82.7	<0.23	112	2.08
Reactive silica (mg/L)	131	133	56	130	93	99
Orthophosphate (mg/L)	10.4	1.3	1.48	0.32	16.55	65.5
TDS (mg/L)	5,380	10,070	5,246	12,080	8,904	3,893
Total hardness (mg/L as $CaCO_3$)	1,840	1,050	2,330	2,470	3,300	1,410
Calcium hardness (mg/L as $CaCO_3$)	1,700	650	1,320	2,180	2,373	918
Alkalinity (mg/L as $CaCO_3$)	968	993	831	401	1,840	1,035
Total chemical oxygen demand (mg/L)	129	39	167	54	228	184
Dissolved chemical oxygen demand (mg/L)	116	42	158	69	208	180
pH	8.5	7.7	7.1	7.9	7.6	7.2
Color at 455 nm (PtCo unit)	145	7	108	<5	354	230
Conductivity (mS/cm)	8.03	15.03	7.83	18.03	13.3	5.8

III.III.II.I PRELIMINARY EXPERIMENT

In preliminary experiments, the light and dark experiment used the following experimental setup. The diatom used was *G. flavovirens* Psetr3. Reactors with light source was under continuous illumination of 15 W, soft white LED bulb. The incubation

temperature was around 22 ºC. The PAR was around 175 µmol m^{-2} s^{-1} at incubation point. Both temperatures and PARs were measured daily to ensure the consistent incubation conditions for all incubators excluding comparison parameters.

For preparation, one 50-mL seed culture (shown in Figure 3-7) with decent amount of biomass was picked and recorded the tube ID. The supernatant was removed from the tube and discarded. Sets of 20 to 200 µL and 100 to 1000 µL micropipettes (VWR) and 10-mL pipettes (Hach) were used for liquid transfer. Based on calculations, 0.5 mL of mixed biomass solution was added to each tube and two microcentrifuge tubes for initial biomass determination. And the final liquid volume was around 3.5 mL, with 0.5 mL of supplementary. Before vortex mix the tube, one glass slide was prepared for initial diatom photo microscopy with a light microscope. Four 50-mL sterile centrifuge tubes and one additional tube for initial parameters concentration determination were prepared and labeled. OCWD ROC was added into tubes using a sterile syringe filter. Then 0.5 mL mixed biomass solution was transferred to four 50-mL tubes and two 1.7-mL microcentrifuge tubes using sterile pipet tips. Then incubated two tubes in the drawer to monitor the dark environment (no light source) and put other two tubes under a clipped lamp. To determine the initial biomass concentration, the 1.7-mL tubes were centrifuged for 30 seconds, then removed and discarded the supernatant with 1 mL pipet. Then added about 1 mL of ultrapure water and vortex mix, then centrifuge again. The wash process was repeated for 10 times. After wash, the 1.7 mL microcentrifuge tubes were placed in a desiccator (shown in Figure 3-8) and weigh the tubes every day until no change in mass.

Figure 3-7. Seed cultures

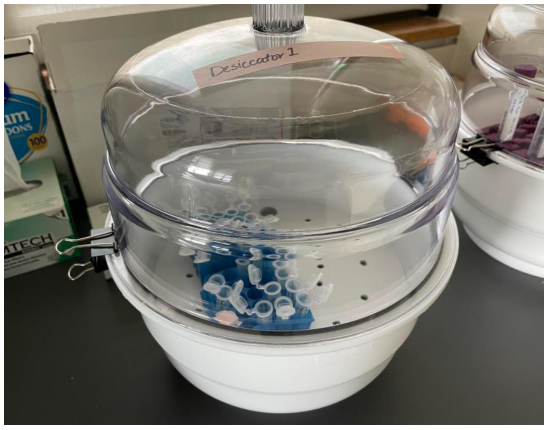


Figure 3-8. Microcentrifuge tubes in desiccator

The silica concentration was tested daily by taking out 1 to 2 mL of sample without disturbing the biomass, and the next cycle was started once approximately 85% of silica uptake was achieved. Corresponding ROCs will be filtered using 0.8/0.2-µm sterile syringe filters and added to the bottles for treatment of next cycle. A list of the water quality parameters was measured at the end of each cycle. After the last cycle, one 1.7 mL microcentrifuge tube was prepared for each sample tube. Photomicrography of diatoms for each tube were took and compared with initial photos to analyze how diatom changed before the photobiological treatment and after varies experimental conditions. Then the biomass was scraped off the bottom of tubes with bamboo skewers and transferred into corresponding microcentrifuge tubes. The biomass was washed 10 times to remove suspended solids, and then put in the desiccator for final biomass concentration determination after dried.

In later experiments like treatability experiment comparing OCWD GWRS and SAWS H2Oaks ROCs and nutrients optimization experiment, reactors were changed to 100-mL coliform polystyrene bottles. Light source was changed to 15 W LED bulbs, soft white (2,700 K). In nutrients optimization experiment, supplementary orthophosphate solution was added to the raw SAWS H2Oaks ROC. Sodium phosphate, anhydrous

(Na_2HPO_4) was used to prepare the 1 g/L orthophosphate stock solution. By calculating the molecular weight of Na_2HPO_4 and PO_4^{3-}, 0.14948 g of anhydrous powder was needed. To prepare the solution, transfer 0.14948 g Na_2HPO_4 powder to the 100 mL volumetric flask by adding ultra-purified water in beaker and making sure the power was completely dissolved and swirled the volumetric flask couple times and mixed completely. Then prepared two sterile 50-mL tubes with proper label, filtered sterilize the stock solution using a 0.8/0.2 μm hydrophilic polyethersulfone membrane syringe filter into the two 50 mL tubes. Covering them with parafilm and stored in the fridge while not in use. The experimental set up procedure was same as the last experiment, unless differences were mentioned. For "no addition" bottle, no additional orthophosphate was added in the incubator. For "+1, +2, +3, +4 mg/L orthophosphate" bottles, add corresponding volume of 1 g/L orthophosphate stock solution to each bottle separately. Then incubate all bottles under same conditions.

III.III.II.II FACTORS INFLUENCE EXPERIMENTS

For factors influence experiments, different experimental conditions were set for varies purposes. In light temperature comparison experiment, the light source was four GE 10 W LED bulbs with different light temperatures (2,700, 3,000, 4,000, and 5,000 K) (Figure 3-9). The incubation temperature was controlled to be within 23.2 to 24 ºC. The PAR was around 200 ± 5 μmol m^{-2} s^{-1} four all four incubators. In light color comparison experiment, light source was 8 W LED colored bulbs from Philips. The incubation temperature was controlled to be within 21 ± 1 ºC. The PARs were set to be within the range of 40 to 50 μmol m^{-2} s^{-1} due to different colors. In order to reach 50 m^{-2} s^{-1} for incubator with blue light, six blue bulbs were used at the same time, while other colors

were only using one bulb. In light intensities comparison experiment, five levels of light intensities (50, 100, 200, 310 and 510 μmol m^{-2} s^{-1}) were controlled by the numbers of 10 W LED bulbs (2,700 K) on the incubators. Due to high light intensities which caused increasing temperature, incubators with PAR equal to 310 and 510 μmol m^{-2} s^{-1} were put in two refrigerated incubators. And the incubation temperature was controlled to be 24 ± 0.2 ºC. In intermittent & continuous light comparison experiment, light source was 10 W LED bulbs, soft white (2,700 K). The intermittent light was controlled by a digital timer which turn one the light automatically at 12:00 PM and turn off at 12:00 AM. The incubation temperature was controlled to be within 22 ± 1 ºC. The PAR was set to be 200 ± 5 μmol m^{-2} s^{-1}. For incubation temperature comparison experiment, the light source was 10 W LED bulbs, soft white (2,700 K). The PAR was set to be 200 ± 5 μmol m^{-2} s^{-1}. The temperatures were set at the specific level ± 0.2 ºC. Two refrigerated incubators were used to set the temperature to 10 °C and 30 °C, and one non-refrigerated incubators was used for 40 °C. The 23 °C was the control setting of the experiment, which provided a more intuitive comparison between different temperatures.

Figure 3-9. Light temperatures comparison experiment (From left: 2,700 K, 3,000 K, 4,000 K, 5,000 K)

Furthermore, due to the potential interference of high concentrations of chloride, sodium and some calcium in SAWS H2Oaks ROC, the nitrate measurements for all SAWS ROC data were imprecise. Based on remeasurements with ultrapure water and thermotical calculation, the final result of nitrate was around 10 mg/L as N, which was comparable to the theoretical concentration by calculation. Therefore, based on the actual value and measurement values, correction factor for nitrate concentration was applied to all the SAWS H2Oaks ROC included experiments.

III.III.II.III TREATABILITY STUDY

For treatability experiment of Hamby WRF, KBHDP, OCWD GWRS CCRO, and WBMWD ROCs, light source was GE 10W LED bulbs, soft white (2,700 K). The incubation temperature was controlled to be within 24 ± 0.5 ºC. The PAR was set to be 200 ± 5 μmol m^{-2} s^{-1}. The water quality parameters of these ROCs were list in the Table 3-5. And experimental procedure follows the same one as in preliminary experiment.

III.III.II.IV OUTDOOR AND *N*-NITROSAMINE REMOVAL INVESTIGATION EXPERIMENT

For this experiment, both LED and sunlight were used as light source for comparisons of *N*-nitrosamine removal. For LED indoor experiment, the set up was the similar with PAR equal to 200 ± 5 μmol m^{-2} s^{-1}. Light source was 10 W LED bulbs, soft white (2,700 K). The incubation temperature was controlled to be within 24 ± 0.5 ºC. The outdoor experiment was conducted in the patio of Roy F. Mitte Building (RFM) 5226 (SMART Lab, Figure 3-10). The experimental set up of both indoor and outdoor experiments were shown in Figure 3-11 and 3-12.

The PAR and temperature were more variable due to the natural environment.

Based on measurement, the PAR was around 400 to 1,800 µmol m^{-2} s^{-1} (with Plexiglas lid) and 30 to 355 µmol m^{-2} s^{-1} (with white lid) at the 1st run. Tables 3-6, 3-7 and 3-8 shows the average temperature, daily PAR and UV measurements, and weather data of the 1st run outdoor experiment. Tables 3-9, 3-10 and 3-11 shows the data for the 2nd run. Tables 3-12, 3-13 and 3-14 shows the 3rd run which had average temperature of 20.9 ± 4.8 ºC, with highest averages of 32.5 ºC and lowest of 15.4 ºC. Both indoor and outdoor experiments had a control jar with no biomass to better compare the photobiological treatment by diatoms.

Figure 3-10. Location of outdoor experiment

Figure 3-11. Indoor experiment set up

Figure 3-12. Outdoor experiment set up

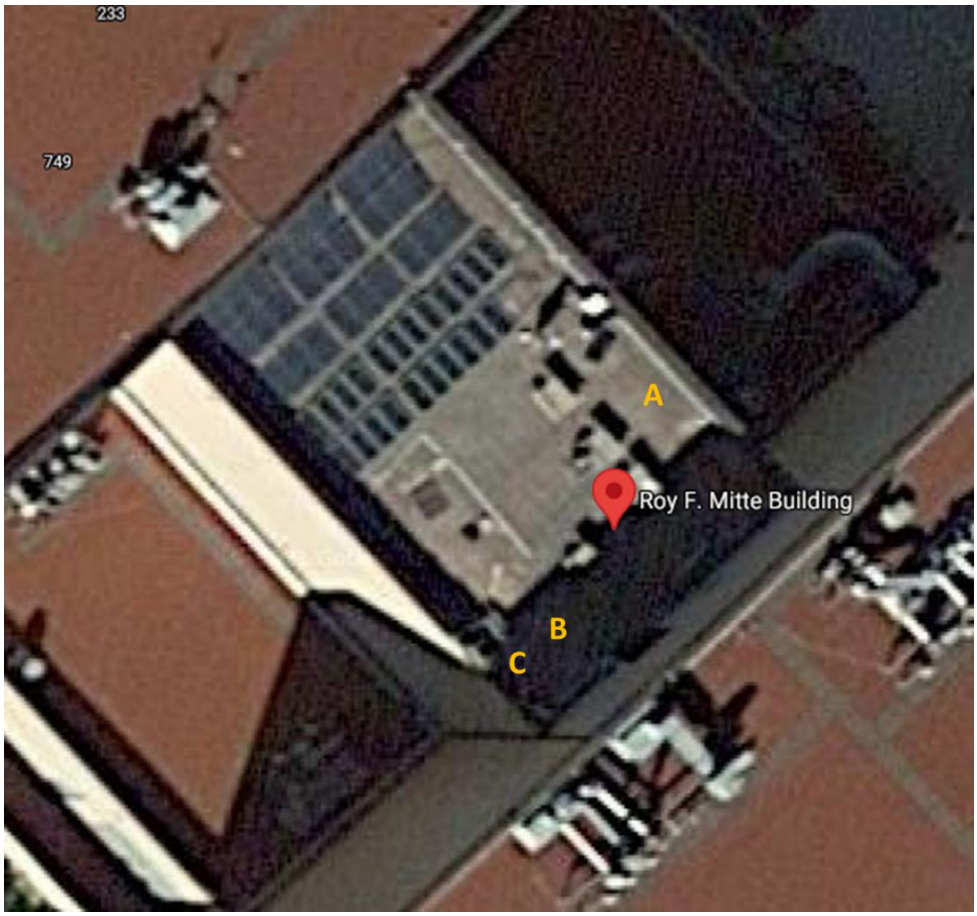


Figure 3-13. Locations of the outdoor experiment setup (A: 1st run; B: 2nd run; C: 3rd run)

Table 3-6. Average temperature data measured by temperature loggers for both outdoor (sunlight) and indoor (LED) experiment (1st run)

	OCWD Sunlight				OCWD LED			
Temperature (°C)	Average	STDEV (±)	High	Low	Average	STDEV (±)	High	Low
Average	19.9	7.0	32.5	11.9	24.0	0.3	24.6	23.6

Table 3-7. Daily PAR and UV measurements (without/with lids) for outdoor experiment (1st run)

Date	**Time**	**PAR without Lid (µmol m^{-2} s^{-1})**	**PAR with Lid (µmol m^{-2} s^{-1})**	**UV without Lid (W m^{-2})**	**UV with Lid (W m^{-2})**
03/06/21	2:00 PM	1,840	1,800	42.4	6.9
03/07/21	1:00 PM	1,792	1,760	41.1	6.7
03/08/21	3:30 PM	470	408	13.1	1.9
03/09/21	11:30 AM	648	117	24.8	0.4
03/10/21	1:00 PM	2,069	354	19.6	0.5
03/11/21	12:30 PM	1,101	184	28.4	0.4
03/12/21	1:00 PM	367	66	8	0.6
03/13/21	11:30 AM	362	54	7.8	0.1
03/15/21	12:30 PM	1,795	264	44.4	0.7
03/16/21	11:30 AM	290	45	8.1	0.1
03/18/21	12:00 PM	1,746	295	41.5	0.5
03/20/21	11:30 AM	1,490	225	34.1	0.6
03/22/21	11:00 AM	176	29	4.8	0.1

Note: 03/06/21 - 03/08/21 (Plexiglas lid), 03/08/21 - 03/22/21 (white lid)

Table 3-8. Weather data for outdoor (sunlight) experiment (1st run) (Weather Underground, 2021; Timeanddate, 2021)

Date	Weather	High (◦C)	Ave. (◦C)	Low (◦C)	Precipitation (Inches)	Sunrise	Sunset	Daylength (h)
03/03/21	Partly Cloudy	22	12.3	2	0	6:55 AM	6:32 PM	11:37:30
03/04/21	Partly Cloudy	25	15.9	5	0	6:53 AM	6:33 PM	11:39:17
03/05/21	Cloudy	27	18.4	12	0	6:52 AM	6:33 PM	11:41:04
03/06/21	Partly Cloudy	20	13.7	6	0	6:51 AM	6:34 PM	11:42:52
03/07/21	Partly Cloudy	21	12	3	0	6:50 AM	6:35 PM	11:44:40
03/08/21	Mostly Cloudy	23	15	5	0	6:49 AM	6:35 PM	11:46:28
03/09/21	Mostly Cloudy	26	18.7	12	0	6:48 AM	6:36 PM	11:48:16
03/10/21	Mostly Cloudy	29	21.9	18	0	6:47 AM	6:37 PM	11:50:04
03/11/21	Mostly Cloudy	27	22.9	21	0	6:45 AM	6:37 PM	11:51:53
03/12/21	Cloudy	28	23.4	21	0	6:44 AM	6:38 PM	11:53:41
03/13/21	Cloudy / Windy	26	22	20	0	6:43 AM	6:39 PM	11:55:30
03/14/21	Light Rain	23	15.9	11	4.32	7:42 AM	7:39 PM	11:57:19
03/15/21	Cloudy	30	17.3	4	0.25	7:41 AM	7:40 PM	11:59:07
03/16/21	Cloudy	28	22.6	19	0	7:40 AM	7:40 PM	12:00:56
03/17/21	Cloudy	26	21.2	13	0	7:38 AM	7:41 PM	12:02:45
03/18/21	Windy	23	14.7	9	0	7:37 AM	7:42 PM	12:04:34
03/19/21	Partly Cloudy	22	13.7	7	0	7:36 AM	7:42 PM	12:06:23
03/20/21	Fair	22	12.4	2	0	7:35 AM	7:43 PM	12:08:12
03/21/21	Cloudy	24	14.4	6	0	7:34 AM	7:44 PM	12:10:01
03/22/21	Cloudy	25	18.5	13	0	7:32 AM	7:44 PM	12:11:50

Note: 03/03/21 - 03/05/21 (1st Cycle for LED), 03/05/21 - 03/07/21 (2nd Cycle for LED)
03/03/21 - 03/08/21 (1st Cycle for Sunlight), 03/08/21 - 03/22/21 (2nd Cycle for Sunlight)

Table 3-9. Average temperature data for outdoor experiment (2nd run)

	OCWD Sunlight			
Temperature (°C)	Average	STDEV (±)	High	Low
Average	27.7	8.5	42.5	17.8

Table 3-10. Daily PAR and UV measurements (without/with lids) for outdoor experiment (2nd run)

Date	**Time**	**PAR without Lid (µmol m^{-2} s^{-1})**	**PAR with Lid (µmol m^{-2} s^{-1})**	**UV without Lid (W m^{-2})**	**UV with Lid (W m^{-2})**
04/08/21	1:00 PM	2,045	624	50.9	1.5
04/09/21	12:00 PM	702	213	20.1	0.6

Table 3-11. Weather data for outdoor (sunlight) experiment (2nd run) (Weather Underground, 2021; Timeanddate, 2021)

Date	**Weather**	**High (◦C)**	**Ave. (◦C)**	**Low (◦C)**	**Precipitation (Inches)**	**Sunrise**	**Sunset**	**Daylength (h)**
04/07/21	Cloudy	29	21.8	10	0	7:13 AM	7:54 PM	12:40:31
04/08/21	Foggy	31	17.9	8	0	7:12 AM	7:54 PM	12:42:17
04/09/21	Partly Cloudy	31	23.8	18	0	7:11 AM	7:55 PM	12:44:02
04/10/21	Cloudy/Windy	26	18.5	9	0	7:10 AM	7:56 PM	12:45:47

Table 3-12. Average temperature data for outdoor experiment (3rd run)

	OCWD Sunlight			
Temperature (°C)	Average	STDEV (±)	High	Low
Average	20.9	4.8	32.5	15.4

Table 3-13. Daily PAR and UV measurements (without/with lids) for outdoor experiment (3rd run)

Date	Time	PAR without Lid (µmol m^{-2} s^{-1})	PAR with Lid (µmol m^{-2} s^{-1})	UV without Lid (W m^{-2})	UV with Lid (W m^{-2})
04/16/21	1:30 PM	104	31	2.9	0.1
04/17/21	12:00 PM	390	139	10.7	0.5
04/18/21	12:30 PM	331	105	8.6	0.2
04/19/21	1:00 PM	221	80	8.6	0.2
04/20/21	12:30 PM	78	24	6.2	0.2
04/21/21	12:30 PM	354	111	11.9	0.4
04/22/21	11:30 AM	164	53	4.4	0.1
04/23/21	12:30 PM	88	25	2.2	0.1
04/24/21	12:00 PM	66	22	5.4	0.2
04/25/21	11:30 AM	68	23	5.5	0.2
04/26/21	1:00 PM	652	184	21.6	0.5
04/27/21	12:00 PM	149	47	4.5	0.1
04/28/21	1:00 PM	262	84	8.9	0.3
04/29/21	10:30 AM	40	13	1.4	0.1
04/30/21	12:30 PM	80	24	2.1	0.1
05/01/21	12:30 PM	76	22	1.9	0.1
05/02/21	1:00 PM	2,033	517	50.2	0.9
05/03/21	1:00 PM	1,971	606	45.8	0.9
05/04/21	11:30 AM	160	49	8.2	0.2
05/05/21	10:30 AM	59	16	5.3	0.1
05/06/21	12:00 PM	76	25	5.2	0.1

Table 3-14. Weather data for outdoor (sunlight) experiment (3rd run) (Weather Underground, 2021; Timeanddate, 2021)

Date	Weather	High (◦C)	Ave. (◦C)	Low (◦C)	Precipitation (Inches)	Sunrise	Sunset	Daylength (h)
04/15/21	Cloudy	21	17.8	16	0	7:04 AM	7:59 PM	12:54:25
04/16/21	Light Rain	20	17.2	15	4.06	7:03 AM	7:59 PM	12:56:07
04/17/21	Cloudy	18	13.5	11	1.02	7:02 AM	8:00 pm	12:57:49
04/18/21	Mostly Cloudy	19	13.2	9	0	7:01 AM	8:00 PM	12:59:30
04/19/21	Mostly Cloudy	23	15.2	6	0	7:00 AM	8:01 PM	13:01:11
04/20/21	Fair/Cloudy	28	16.6	7	0	6:59 AM	8:02 PM	13:02:50
04/21/21	Mostly Cloudy	17	11.5	6	0	6:58 AM	8:02 PM	13:04:30
04/22/21	Cloudy	18	14	4	0	6:57 AM	8:03 PM	13:06:08
04/23/21	Cloudy/Foggy	22	18.9	16	0	6:56 AM	8:04 PM	13:07:46
04/24/21	Fair	28	20.7	14	14.22	6:55 AM	8:04 PM	13:09:24
04/25/21	Cloudy	29	20.6	9	0	6:54 AM	8:05 PM	13:11:00
04/26/21	Mostly Cloudy	29	22.2	18	0	6:53 AM	8:06 PM	13:12:36
04/27/21	Cloudy	26	22.9	21	0	6:52 AM	8:06 PM	13:14:11
04/28/21	Cloudy	29	25	22	0	6:51 AM	8:07 PM	13:15:45
04/29/21	Light Rain	24	21.5	19	2.79	6:50 AM	8:07 PM	13:17:18
04/30/21	Cloudy	22	19.7	18	1.52	6:49 AM	8:08 PM	13:18:51
05/01/21	Storm	22	19.5	18	50.55	6:48 AM	8:09 PM	13:20:22
05/02/21	Cloudy/Foggy	30	21.6	14	35.81	6:47 AM	8:09 PM	13:21:53
05/03/21	Cloudy	33	25.2	21	0	6:47 AM	8:10 PM	13:23:22
05/04/21	Mostly Cloudy	26	22.2	17	0	6:46 AM	8:11 PM	13:24:51
05/05/21	Fair	25	18.6	12	6.35	6:45 AM	8:11 PM	13:26:18
05/06/21	Fair	29	19.9	11	0	6:44 AM	8:12 PM	13:27:45

Note: 04/15/21 - 04/24/21 (1st Cycle), 04/24/21 - 04/29/21 (2nd Cycle), 04/29/21 – 05/06/21 (3rd Cycle)

The 500-mL polycarbonate jars were disinfected with 100 mg/L (as Cl_2) diluted bleach solution. After inverted the jar with lid several times, placed in the biosafety cabinet for around one hour. And then prepared about 200 mL of filter sterilized ultrapure water with a sterile 0.2/0.8 μm syringe filter. Emptied the jars and tap dry. Then rinsed both jars and lids three times with filtered ultrapure water. At the end, left them upside down in the cabinet overnight, and stored them after dried. Vacuum filtration was used for ROC preparation. For prefiltration, PYREX 500-mL volumetric flask, HACH filter funnel (Loveland, CO), and VWR TSS glass fiber filter with pore size of 1.5 μm (diameter 70 mm) were used. After that, secondary filtration used another flask, magnetic filter funnel (Pall Corporation, US), and VWR 0.45 μm, 47 mm versapor filter membrane. Then the filtered ROC was transferred to the jars for further preparation. Samples for *N*-nitrosamine analysis were collected in HPLC vials (VWR Vials and Closures Convenience Kits for Shimadzu HPLC Autosamplers) at each preparation stages: before filtration, PTFE filtered sample; after vacuum filtration; daily supernatant, PTFE filtered sample; supernatant after end of each cycle, PTFE filtered. The purpose of this was to see if *N*-nitrosamines were removed or lost by any of the preparation steps.

IV. RESULTS AND DISCUSSIONS

IV.I. PRELIMINARY EXPERIMENTS

To better comparing the difference between varies experimental settings, the definition of silica uptake rate was discussed and determined for future purposes. Figure 4-1 shows the silica uptake in three cycles for OCWD GWRS and SAWS H2Oaks ROCs. In the first cycle, there was usually two to three days delay of the photobiological treatment for both ROCs, and then the removal started. As modeled in Figure 4-2, the removal trend can be either 1^{st} or 0^{th} order. Then in the second and third cycles, the silica uptake started without lag period and followed the 0^{th} order, which was a straight line, excepting the second half of SAWS H2Oaks ROC that stopped working due to some reasons explained in the later section. Therefore, based on the common conditions in later experimental results, the 0^{th} order kinetics model was used in my research to calculate the silica uptake rate. Figure 4-3 shows the Figure 4-1 with red arrows, which indicated how the silica uptake rate was calculated.

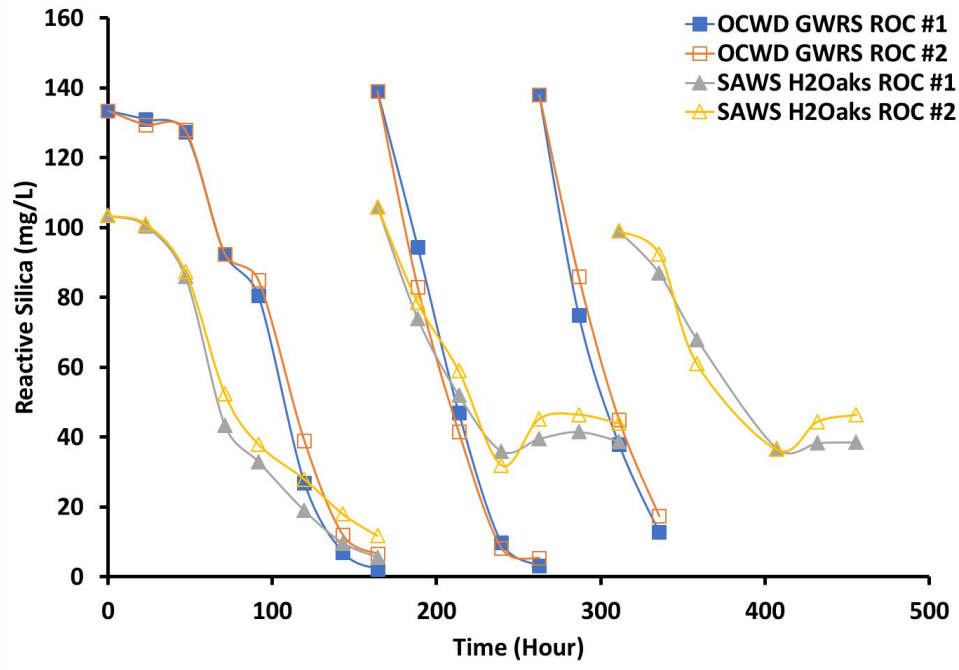


Figure 4-1. Three cycles of photobiological treatment in OCWD GWRS and SAWS H2Oaks ROCs

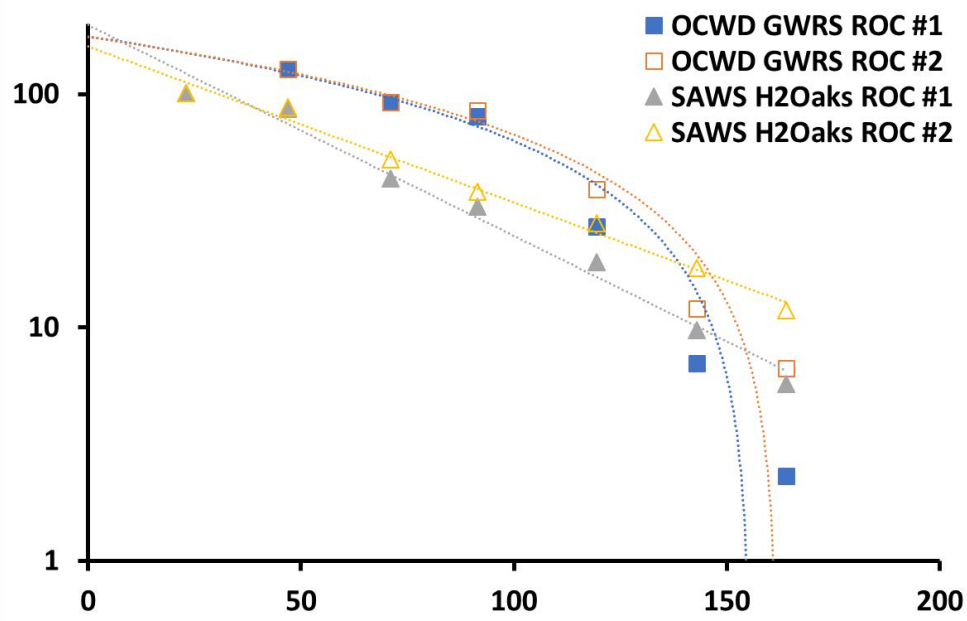


Figure 4-2. Logarithmic scale of the Figure 4-1

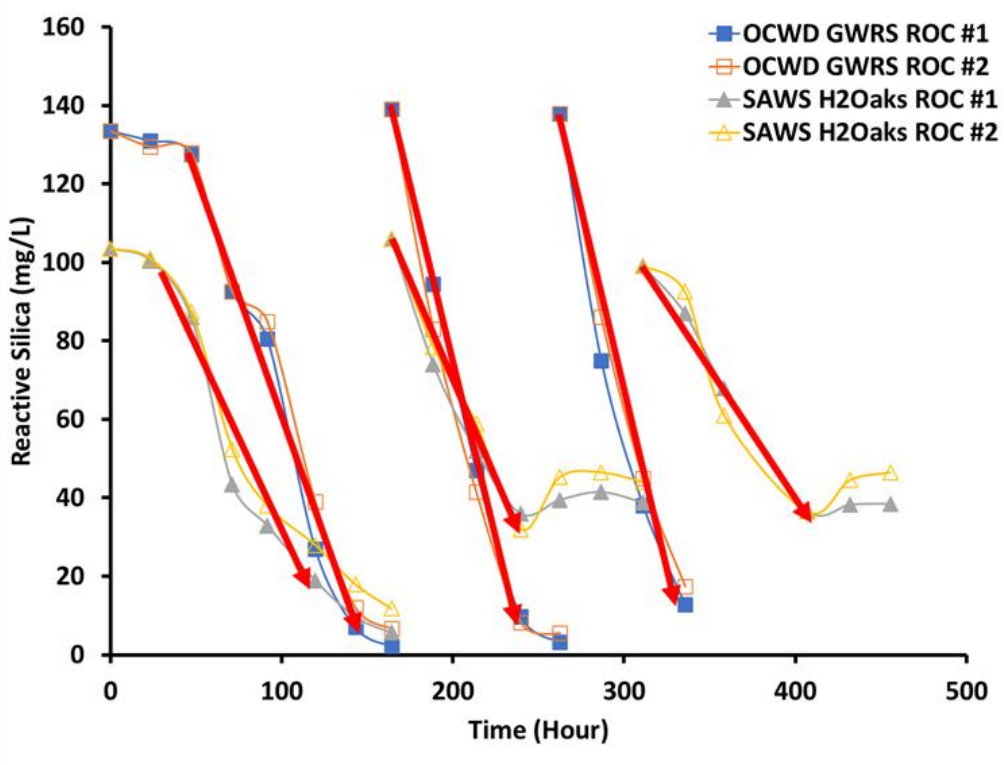


Figure 4-3. Silica uptake rates shown by red arrows

IV.I. I. LIGHT & DARK EXPERIMENT

Figure 4-4 shows the result of the bench-scale experiment comparing light and dark incubation environment in terms of silica uptake in the 50-mL polypropylene centrifuge tubes. There were four 50-mL tubes, with two under continuous illumination of a light source (an LED blub) while the other two were incubated in a dark environment. The reactive silica concentration decreased from 126 mg/L to less than 6 mg/L in incubators with a light source in less than 192 hours (8 days). The tubes in the dark environment did not show a decreasing trend for more than 150 hours. Furthermore, the biomass concentration in light condition increased 9.5 times than initial (before treatment) concentration, while there was no remarkable increase in the tubes under dark environment. This experimental result indicated that the light is an essential source of energy for silica uptake process. Uptake of silica is within the period of cell cycle following cytokinesis and prior to the separation of two cells (Sullivan, 1977). During photosynthesis, it can produce carbohydrates and oxygen, and this provided energy for diatom to process growth, such as increase cell size and produce new cells, where the silica is taken up (Harvenda et al., 2019). Although silicification is more related to aerobic respiration and has no direct involvement of energy from photosynthesis (R.E. Lee, 2008, p. 374), the silica was taken up indirectly from photosynthesis.

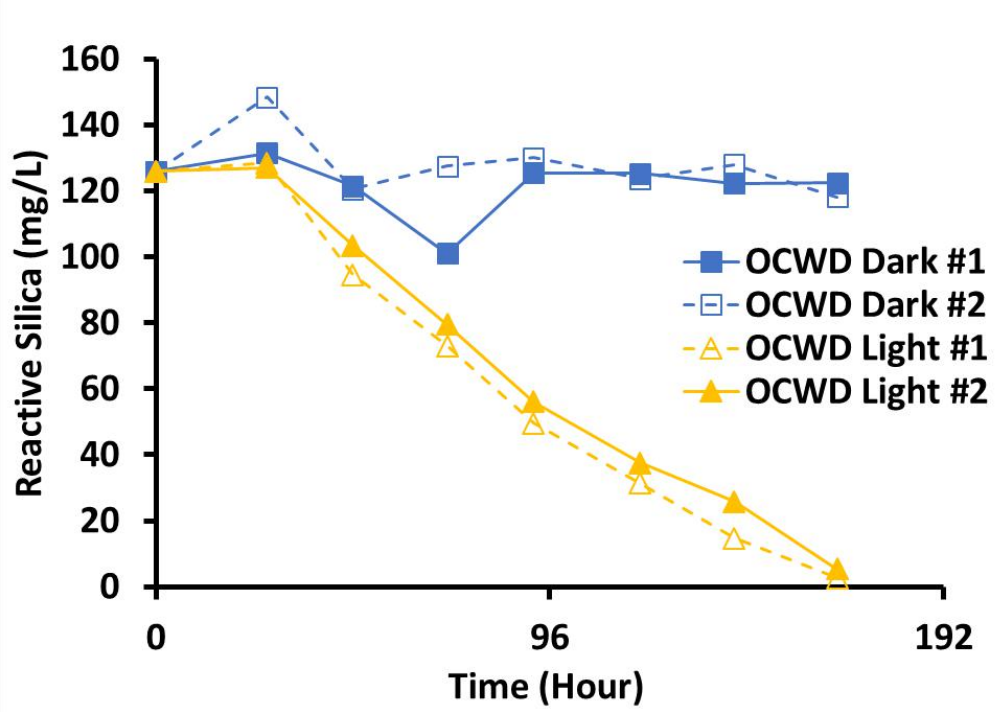


Figure 4-4. Reactive silica removal from OCWD GWRS ROC in dark/light conditions by the photobiological treatment
(Temperature: 22 ± 2 °C, PAR: 175 µmol m^{-2} s^{-1}, 15 W Great Value LED, 2,700 K, initial biomass concentration: 0.176 g/L)

After the above experiment, the tubes in the dark environment were moved to the places with the same illumination condition as the light tubes. Figure 4-5 shows the silica uptake in this experiment. After around 143 hours of lag period, diatoms in the tubes previously under the dark started to take up silica slowly and reached less than 3 mg/L of final dissolved silica concentration after 288 hours. This result shows that the diatoms were capable to restore after some lag period and started to take up silica with light source. Furthermore, as shown in Figure 4-6, the result of light tubes indicates that this silica uptake procedure is repeatable for at least three cycles.

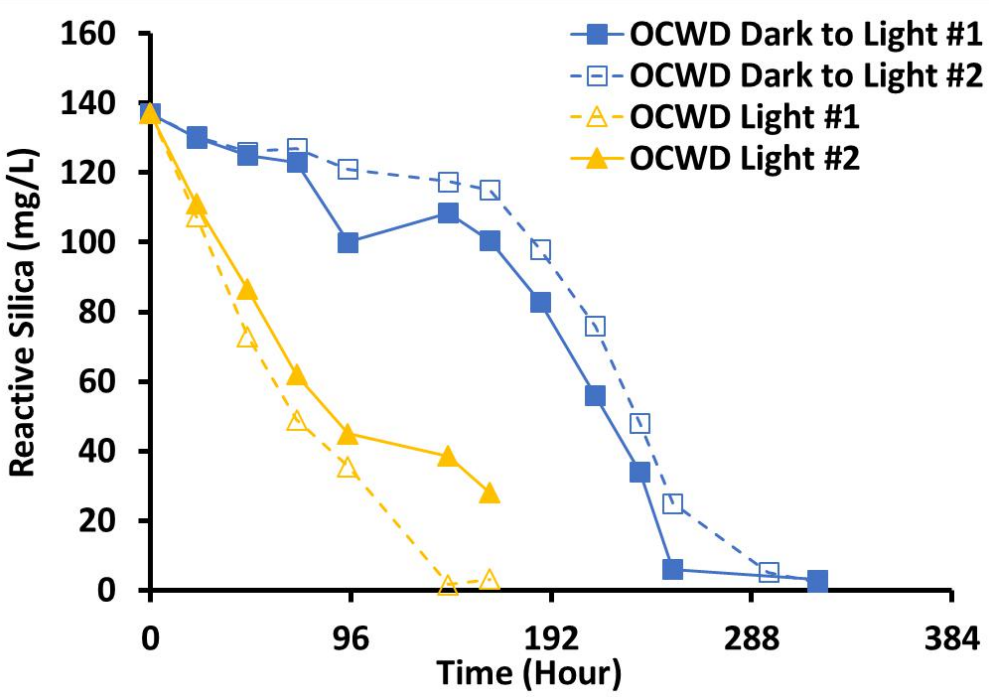


Figure 4-5. Reactive silica removal from OCWD GWRS ROC in light conditions by the photobiological treatment
(Temperature: 22 ± 2 °C, PAR: 175 µmol m^{-2} s^{-1}, 15 W Great Value LED, 2,700 K, initial biomass concentration: 0.176 g/L)

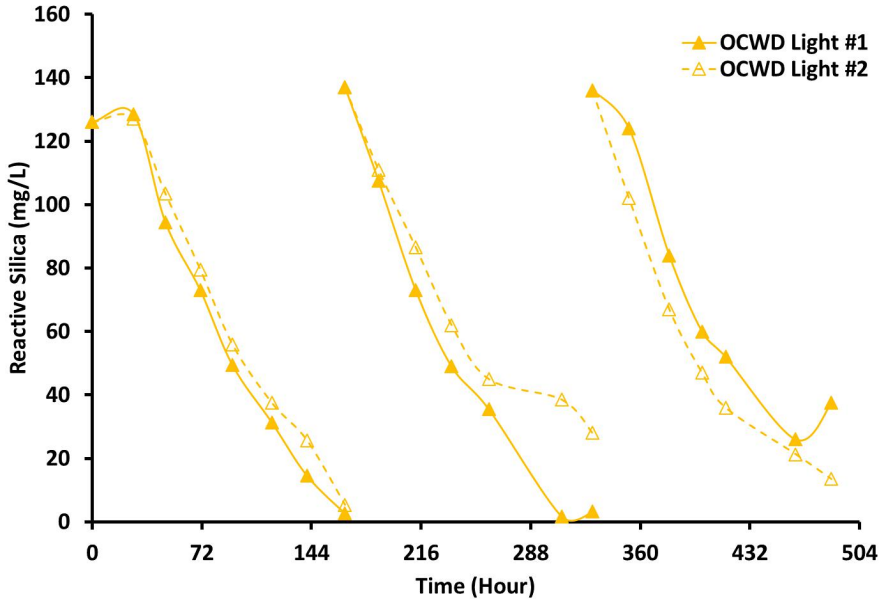


Figure 4-6. Reactive silica removal from OCWD GWRS ROC in light conditions by the photobiological treatment

(Temperature: 22 ± 2 °C, PAR: 175 μmol m^{-2} s^{-1}, 15 W Great Value LED, 2,700 K, initial biomass concentration: 0.176 g/L)

Figure 4-7 shows the percentage removal of silica, ammonia-N, orthophosphate, and nitrate-N after two to three cycles of photobiological treatment in the OCWD GWRS ROC. For light tubes, all three cycles reached >80% removal in silica, ammonia-N and orthophosphate. Nitrate-N removal was around 10%, which may be due to sufficient nitrogen source from ammonia. At first cycle, tubes under the dark environment had less than 10% silica removal. Although the silica removal was small, nutrients like ammonia-N and orthophosphate were removed by 10% and 40%, respectively, after the first cycle in the dark. This indicated that diatoms would take up some nutrients (mainly ammonia and orthophosphate) even without performing photosynthesis. At the beginning of the second cycle, those tubes were moved to places with the same illumination sources as the light tubes. After 288 hours (12 days), removal reached >90% for all three parameters exclude nitrate-N, which was not used preferentially in this experiment. This shows that the diatoms can restore growth after a period of hiatus in the dark, and to take up silica and nutrients for their growing processes with light source.

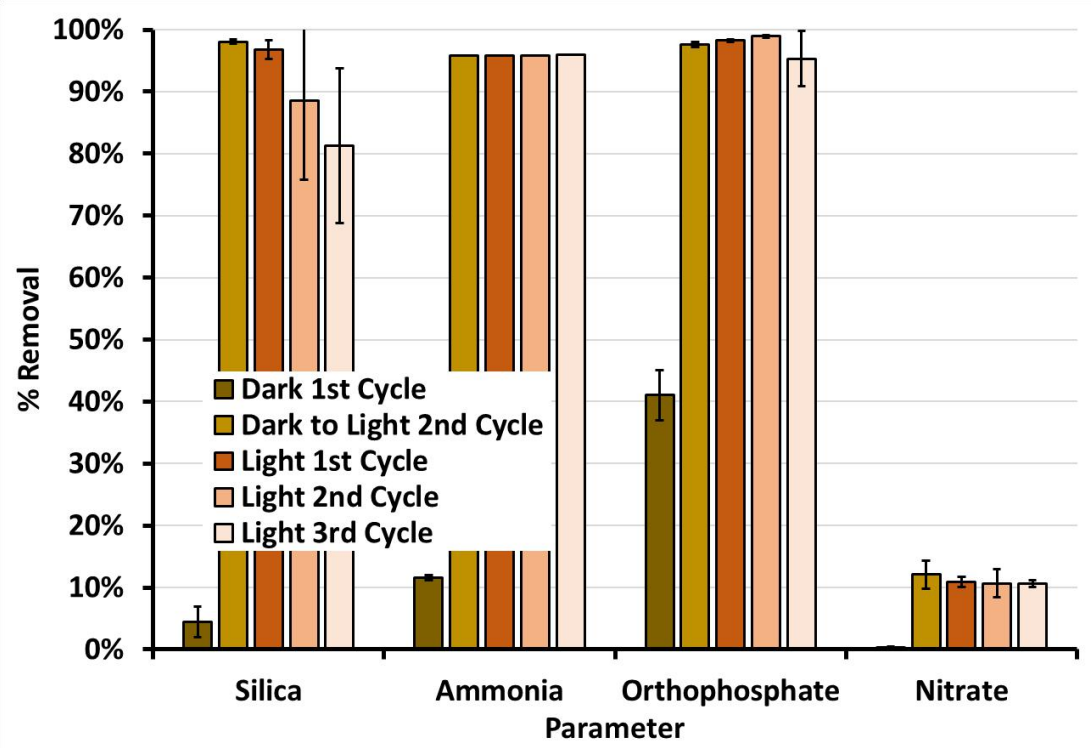


Figure 4-7. Percentage removal of silica and nutrients after two or three cycles from OCWD GWRS ROC by the photobiological treatment
(See Figure 4-4, 4-5 or 4-6 for experimental conditions)

IV.I. II. OCWD GWRS AND SAWS H2OAKS ROCS COMPARISON EXPERIMENT

Figure 4-8 shows the silica uptake during the treatability study of OCWD GWRS ROC. There was a lag period from 0 to 48 hours at the beginning of the experiment. The causes could be experimental techniques since the biomass were injected into the bottle incubator with pipet, and it took some time for them to sink to the bottom before they start to take up silica. After the lag time, silica concentration started to decrease to <10 mg/L after 144 hours (6 days) of incubation.

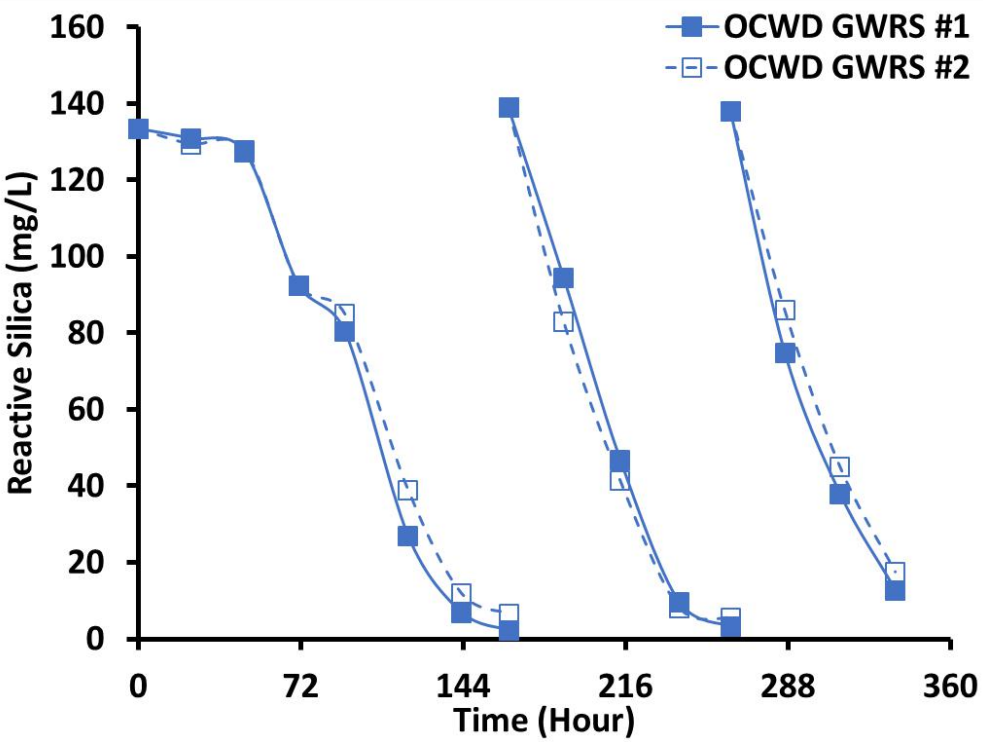


Figure 4-8. Three cycles of the photobiological treatment in OCWD GWRS ROC (Temperature: 22 ± 2 °C, PAR: 175 µmol m^{-2} s^{-1}, 15 W Great Value LED, 2,700 K, initial biomass concentration: 0.187 g/L)

Furthermore, the result indicates that the silica uptake was repeatable, and silica removal could reach >85% at end of each cycle. Figure 4-9 is the silica uptake rate in

mg/L/day for the three cycles. The uptake rates increased from 25 mg/L/day in the first cycle to 41 mg/L/day in the last cycle, which showed that after a period of growth, more biomass was formed, and more dissolved silica had been taken up in the same time duration (in daily base). This is a common situation that was found in later experiments.

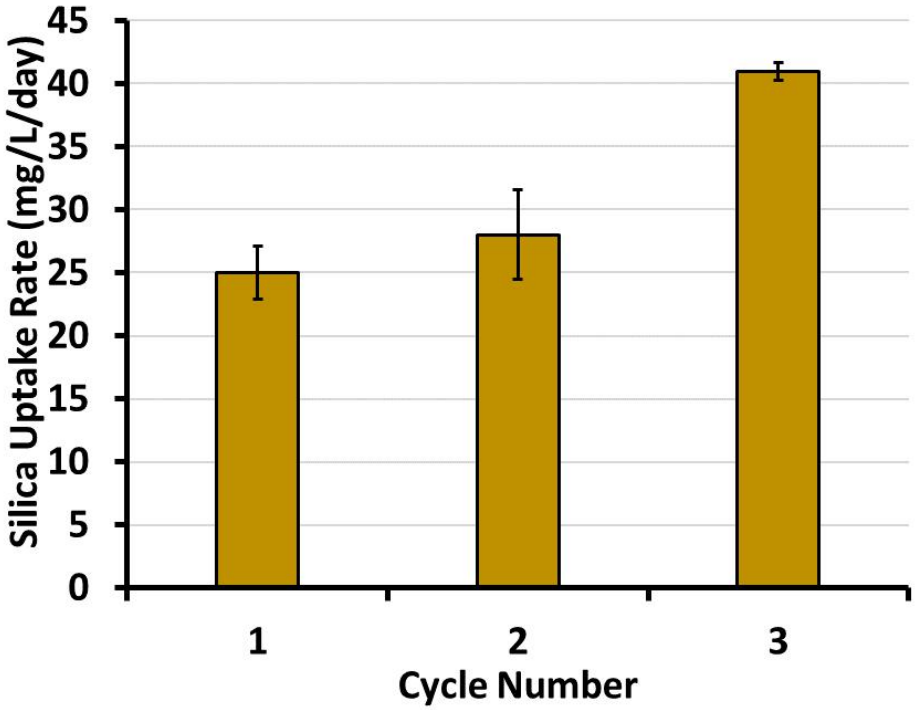


Figure 4-9. Three cycles of silica uptake rates in OCWD GWRS ROC (Temperature: 22 ± 2 °C, PAR: 175 µmol m^{-2} s^{-1}, 15 W Great Value LED, 2,700 K, initial biomass concentration: 0.187 g/L)

Figure 4-10 shows the three cycles of experimental results in the treatability study of SAWS H2Oaks ROC. In comparison to the OCWD GWRS treatability study, the lag period with this ROC was relatively short (~1 day). This might be due to the differences in water quality parameters between these two ROCs. Since SAWS H2Oaks ROC was from a groundwater desalination plant while OCWD GWRS ROC was from an advanced water purification facility. Unlike the first cycle, which reached >85% of silica removal at the end, both the second and third cycles stopped taking up silica at around 38 to 47

mg/L SiO_2. Table 4-1 below shows the silica and nutrients concentrations for the initial (before) and after treatment in SAWS H2Oaks ROC. Since there was no nitrate-N in this ROC, ammonia-N and orthophosphate were the primary nutrients for the photobiological treatment. The supernatant of all three cycles shows <0.5 mg/L of ammonia-N and orthophosphate, even for the second and third cycles, where silica uptake did not complete. Based on the analysis of water quality parameters, it might be due to insufficient nutrients (mainly orthophosphate) in the ROC which originated from groundwater and contained very limited nutrients. Therefore, it was speculated that completing the silica removal of three cycles may require additional nutrients. According to the previous study (Kulkarni et al., 2019), supplementary orthophosphate and nitrate would support the diatoms to achieve ideal silica uptake, however, a high concentration of ammonia-N was found to be inhibitory to diatom growth.

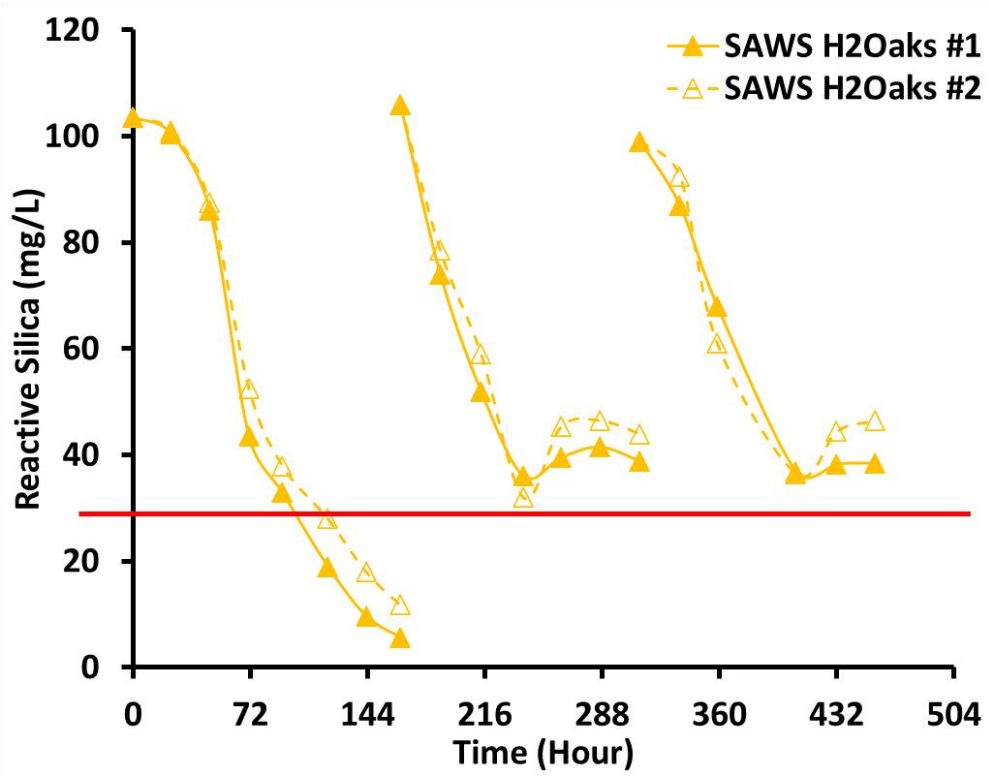


Figure 4-10. Three cycles of photobiological treatment in SAWS H2Oaks ROC treatment (Temperature: 22 ± 2 °C, PAR: 175 µmol m^{-2} s^{-1}, 15 W Great Value LED, 2,700 K, initial biomass concentration: 0.187 g/L)

Table 4-1. Average silica and nutrients concentrations (3 cycles) in SAWS H2Oaks ROC (collected on August 22, 2019) before and after treatment

Parameter	Initial	1st Cycle	2nd Cycle	3rd Cycle
Silica (mg/L SiO_2)	103	9	41	36
Nitrate (mg/L as N)	<0.23	<0.23	<0.23	<0.23
Ammonia (mg/L as N)	8.6	< 0.4	< 0.4	< 0.4
Orthophosphate (mg/L as PO_4^{3-})	1.7	0.25	0.08	0.08

Figure 4-11 shows the percentage removal of four water quality parameters after the photobiological treatment. For dissolved silica concentration, three cycles of OCWD GWRS ROC and the first cycle of SAWS H2Oaks ROC reached >85% of silica removal. Since orthophosphate and ammonia are the preferred N and P sources of nutrients (Ikehata et al., 2017), both ROCs and all cycles achieved >80% of removal of these nutrients. Nutrient removal is important in my research where ROCs from AWPFs were treated. Since excessive nitrogen and phosphorus are two main pollutants in ocean/surface water discharge, which may cause water quality deterioration and environmental issues (Li et al., 2010; Wang et al., 2016). However, for brackish groundwater ROC like SAWS H2Oaks, nutrients concentrations should be kept in a level that can sustain the diatom growth and the photobiological treatment of removing silica. Conductivity, which related to TDS, also decreased 10 to 30% with OCWD GWRS ROC and 3 to 12% with SAWS H2Oaks ROC. This is mainly due to the precipitation of calcium carbonate (see below). This will also help reducing scaling in the secondary RO.

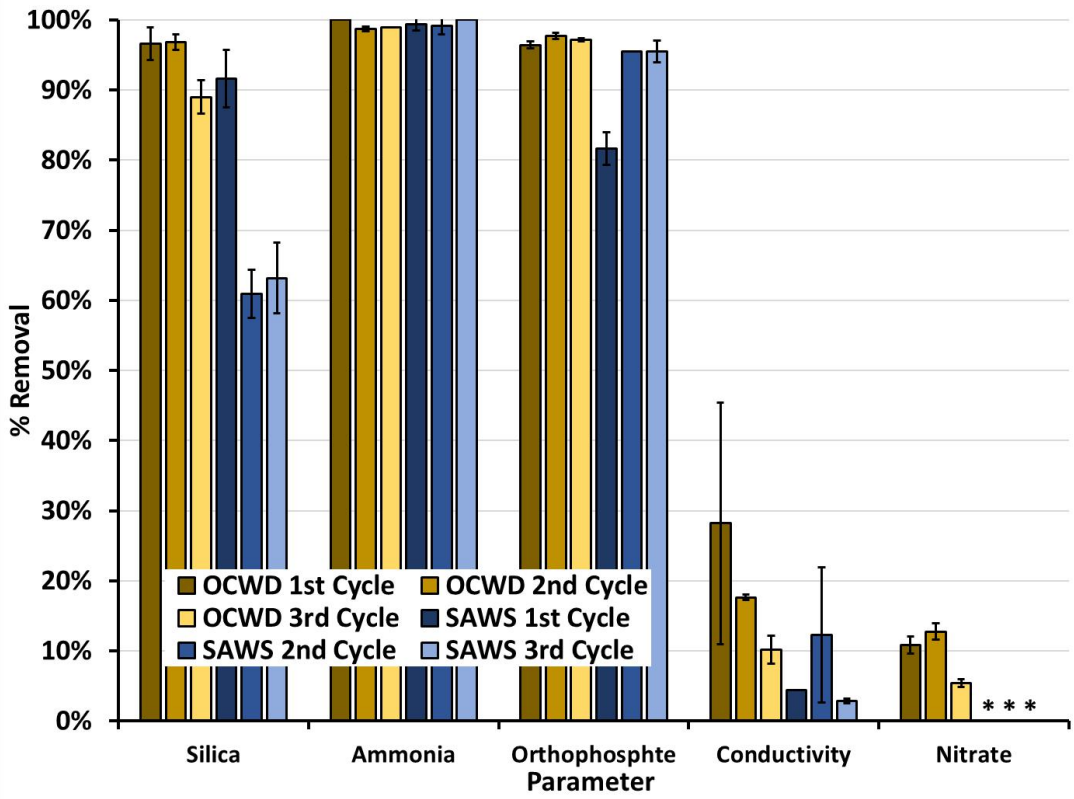


Figure 4-11. % Removal of five water quality parameters after the photobiological treatment in OCWD GWRS and SAWS H2Oaks ROCs, *<1%
(See Figures 4-8, 4-9 and 4-10 for the experimental conditions)

In Figures 4-12 and 4-13, which shows the total, calcium hardness and alkalinity removal by the photobiological treatment in the OCWD GWRS and SAWS H2Oaks ROCs. Since total hardness equal to calcium harness and magnesium hardness, and magnesium was not removed by the photobiological treatment, the removed concentration (as mg/L of $CaCO_3$) should be around the same for all three parameters. There might be some analytical errors in the measurements, but the difference is within 200 mg/L. Microalgae such as diatom was known to remove hardness and alkalinity (Borowitzka & Larkum, 1987), along with other parameters such as the scalant, silica. The photobiological process of diatom growth increased the pH of water sample by absorbing carbon dioxide (CO_2) for photosynthesis (Ikehata et al., 2017), then

bicarbonate and calcium were removed by forming calcium carbonate ($CaCO_3$) precipitate in the samples (Borowitzka & Larkum, 1987). However, magnesium hardness was not removed by the photobiological treatment, but it can be removed by calcium hydroxide ($Ca(OH)_2$) which raises pH to 11 or higher. Therefore, total hardness was not measured in the later experiments.

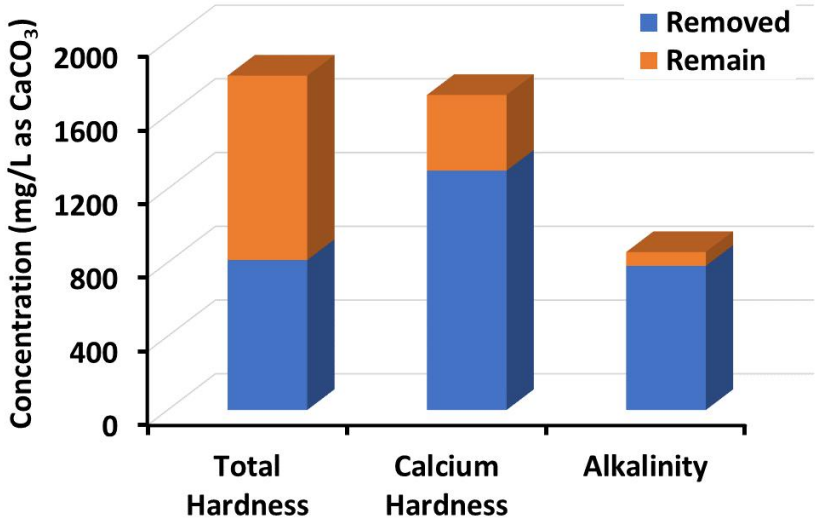


Figure 4-12. Hardness and alkalinity removal in OCWD GWRS ROC
(See Figures 4-8, 4-9 and 4-10 for the experimental conditions)

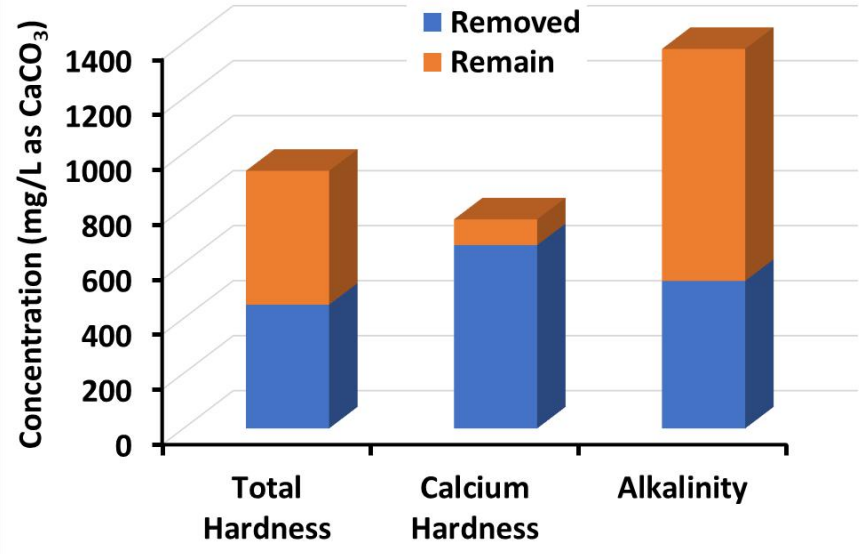


Figure 4-13. Hardness and alkalinity removal in SAWS H2Oaks ROC
(See Figures 4-8, 4-9 and 4-10 for the experimental conditions)

IV.I. III. NUTRIENTS OPTIMIZATION EXPERIMENT

Based on the results in the previous experiment, a nutrients optimization experiment was conducted to determine the amount of supplementary nutrients needed for repeatable semi-batch photobiological treatment in SAWS H2Oaks ROC. Figure 4-14 shows the impacts of different concentrations of orthophosphate addition on the silica uptake rates by the photobiological treatment. The first cycle of this photobiological treatment was completed (>85% silica removal) regardless of orthophosphate addition, which was consistent with the previous treatability experiment (Figure 4-10). In the second cycle, there was a slightly slowdown in the middle for no additional orthophosphate condition. Yet, the photobiological treatment was completed in this ROC without orthophosphate addition (open squires), which did not happen in the previous experiment. In this case, the ROC was freshly collected on March 23, 2020, which had ammonia-N concentration of around 8.5 mg/L and orthophosphate concentration of 1.6 mg/L as PO_4^{3-} (shown in Table 4-2).

Table 4-2. Average silica and nutrients concentrations in SAWS H2Oaks ROC (sample collected date: March 23, 2020; second measurements: July 1, 2020)

Date	Silica (mg/L SiO_2)	Nitrate (mg/L as N)	Ammonia (mg/L as N)	Orthophosphate (mg/L as PO_4^{3-})
March 23, 2020	133	<0.23	8.5	1.6
July 1, 2020	130	<0.23	3	1.5

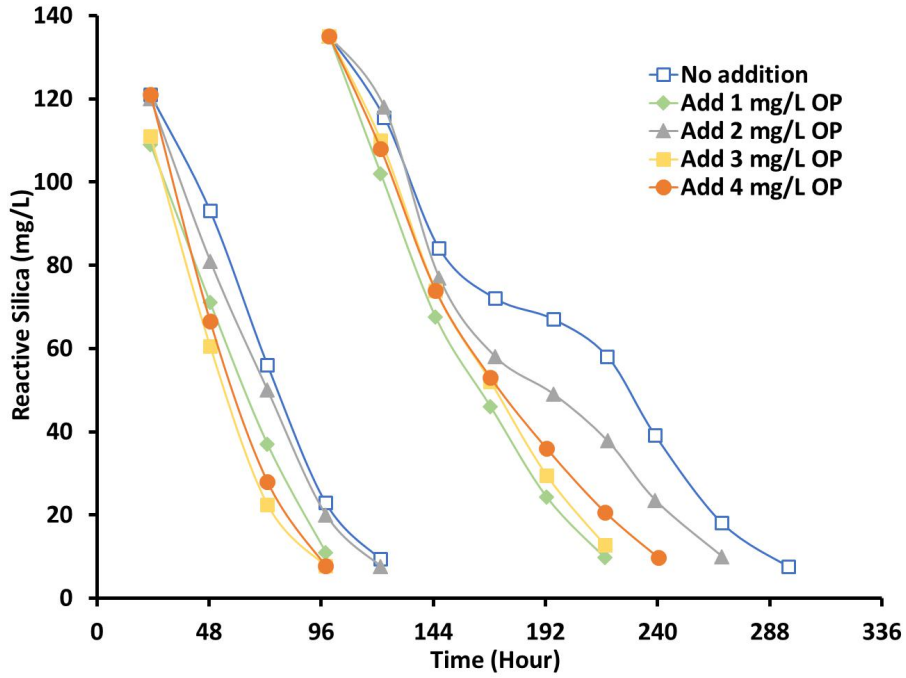


Figure 4-14. Impact of orthophosphate (OP) addition on the silica uptake in SAWS H2Oaks ROC by brackish diatom *G. flavovirens* Psetr 3
(Temperature: 22 ± 2 °C, PAR: 175 µmol m^{-2} s^{-1}, 15 W LED, 2,700 K, initial biomass concentration: 0.63 g/L)

To further investigate the nutrient requirements for raw SAWS H2Oaks ROC with no additional orthophosphate could complete the treatment, another experiment was conducted to compare the silica uptake between no addition and add 1 mg/L orthophosphate in the SAWS H2Oaks ROC. As shown in Figure 4-15, both conditions finished the first cycle, but stopped taking up silica at the second cycle. The experiment was conducted on July 1st, 2020 (shown in Table 4-2) with the same ROC used in previous experiment (Figure 4-14), the ammonia-N concentration was decreased from 8.5 mg/L in previous experiment to around 3 mg/L in this experiment. This might be due to the long-time sample storage in the laboratory, and ammonia-N was lost via volatilization. Combing the results from previous experiment (Figure 4-10), it was concluded that both orthophosphate and nitrogen could be the limiting factors for the repeatable

photobiological treatment especially for long-time storage ROC which lost ammonia-N.

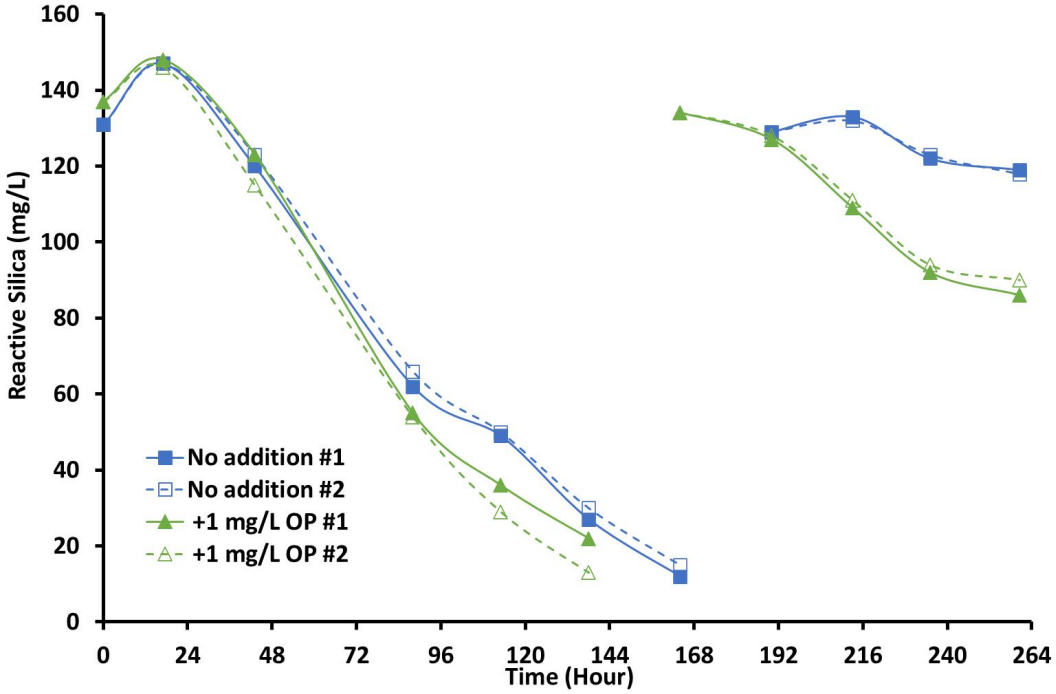


Figure 4-15. Impacts of with/without orthophosphate (OP) addition on the silica uptake in SAWS H2Oaks ROC by brackish diatom *G. flavovirens* Psetr 3
(Temperature: 22 ± 2 °C, PAR: 175 µmol m^{-2} s^{-1}, 15 W LED, 2,700 K, initial biomass concentration: 0.051 g/L)

Several additional experiments were conducted to confirm the repeating high silica uptake in the SAWS H2Oaks ROC lack sufficient nutrients (mainly N and P). The supernatant from most cycles shows that the final ammonia-N and orthophosphate concentrations were less than 0.5 mg/L, even for cycles which did not reach 85% removal or those stopped working in the middle. Therefore, the impacts of adding orthophsphate only and adding both orthophsphate and nitrate-N on the silica uptake rate in the SAWS H2Oaks ROC were investigate. Table 4-3 shows the nutrients data for raw sample and after added algae food and orthophaphate stock solution. As shown in Figure 4-16, the result indicated that the photobiological treatment of SAWS H2Oaks ROC could be completed with supplementary ~2 mg/L of orthophosphate and ~5 mg/L of nitrate-N.

Although addition of 2 mg/L of orthophosphate was able to finish silica removal for two cycles in previous experiment (Figure 4-14), it did not continue at the middle this time and got a flat trend which shows that nutrients were insufficient. Also, since F/2 Algae food was used in previous experiments with brackish groundwater ROC treatment (Ikehata et al., 2018a), it was also used in my study based on the similar case. Due to some restrictions, ROCs were collected and stored in refrigerators which orthophosphate and ammonia-N might gradually lost. Therefore, supplementary 4 mg/L of orthophosphate and 10 mg/L of nitrate-N were added to SAWS H2Oaks ROC (as well as other brackish groundwater ROCs) to ensure that sufficient nutrients were available for the photobiological treatment in the subsequent experiments.

Table 4-3. Concentrations after adding 0.2 mg/L of AF and OP in SAWS H2Oaks ROC

Parameters	**Raw**	**+ AF**	**+ OP**
Nitrate (mg/L as N)	< 0.23	5	< 0.23
Ammonia (mg/L as N)	3	3	3
Orthophosphate(mg/L as PO_4^{3-})	1.5	3.5	3.6

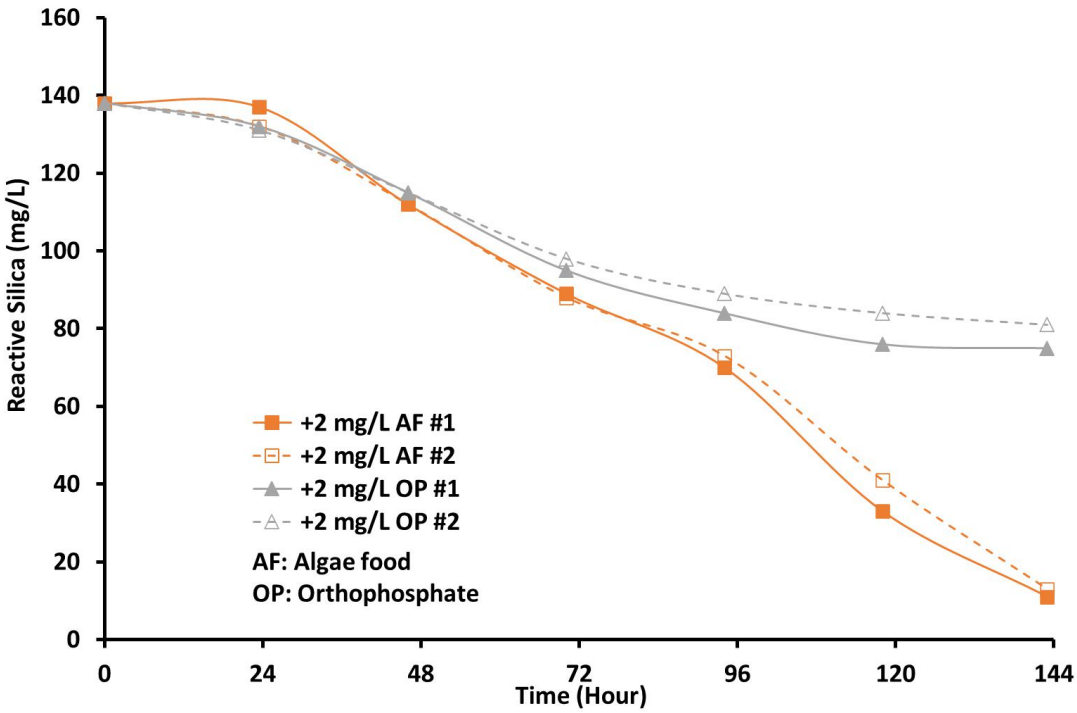


Figure 4-16. Impacts of orthophosphate addition only and both orthophosphate and nitrate on silica uptake in SAWS H2Oaks ROC

(Temperature: 22 ± 2 °C, PAR: 175 µmol m^{-2} s^{-1}, 15 W LED, 2,700 K, initial biomass concentration: 0.051 g/L)

IV.II. FACTORS INFLUENCE & COMPARISON EXPERIMENTS

In this series of experiments, different critical parameters such as light temperatures, colors, intensities, photoperiod, and incubation temperatures were conducted to systematically investigate the impact of how these influences the biological process of the diatom, and silica uptake rate. By understanding the impacts of these parameters, enhancement of silica uptake rate may be achieved, and thus shorten hydraulic retention time and reduce the capital cost of the photobiological process.

IV.II. I. LIGHT TEMPERATURES EXPERIMENT

Figure 4-17 shows the first cycle results of different light temperatures comparison for OCWD GWRS ROC. Besides some lag period at the beginning of all four levels of light temperatures, they exhibited comparable silica uptake rates during the photobiological treatment. The longer lag period in OCWD 4,000 K #1 may be due to technical errors such as pipette or mixing. Figure 4-18 shows the second cycle of this experiment, which indicates that there is nearly no difference in terms of silica uptake between those four levels. Figure 4-19 shows the average silica uptake rates for the two cycles treatment. The silica uptake rates were all around 40 mg/L regardless of the light temperatures. This condition was more apparent in Figure 4-20, which is the experimental results of light temperatures comparison for SAWS H2Oaks ROC. The silica uptake rates were around 35 mg/L/day for all the light temperatures.

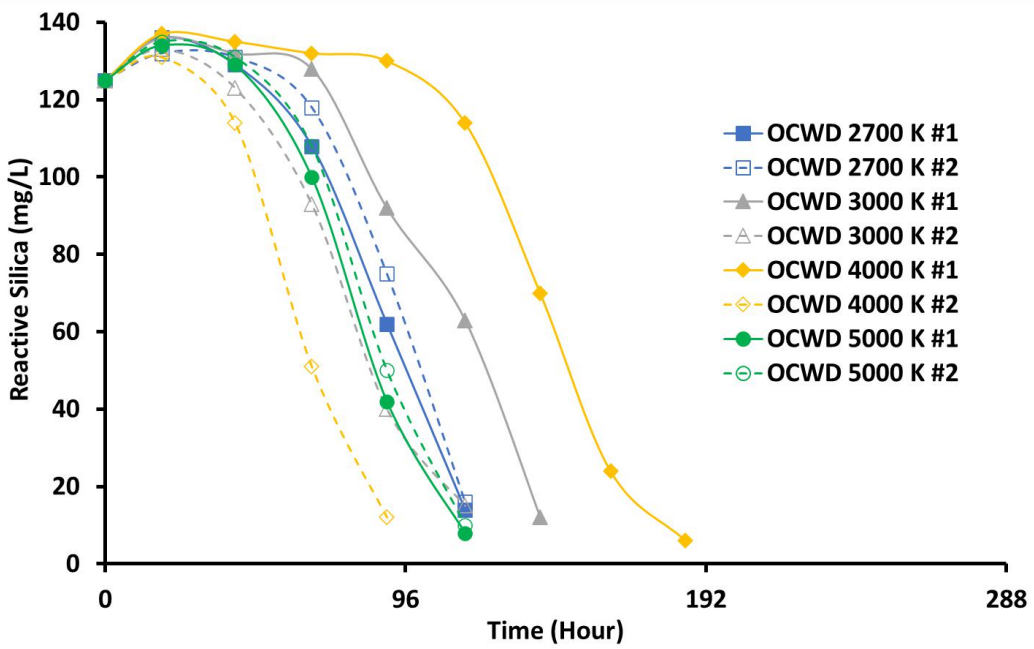


Figure 4-17. Light temperatures comparison in terms of silica uptake with OCWD GWRS ROC in the first cycle
(Temperature: 23 ± 1 °C, PAR: 200 ± 5 µmol m^{-2} s^{-1}, 10 W LED, 2,700, 3,000, 4,000, 5,000 K, initial biomass concentration: 0.127 g/L)

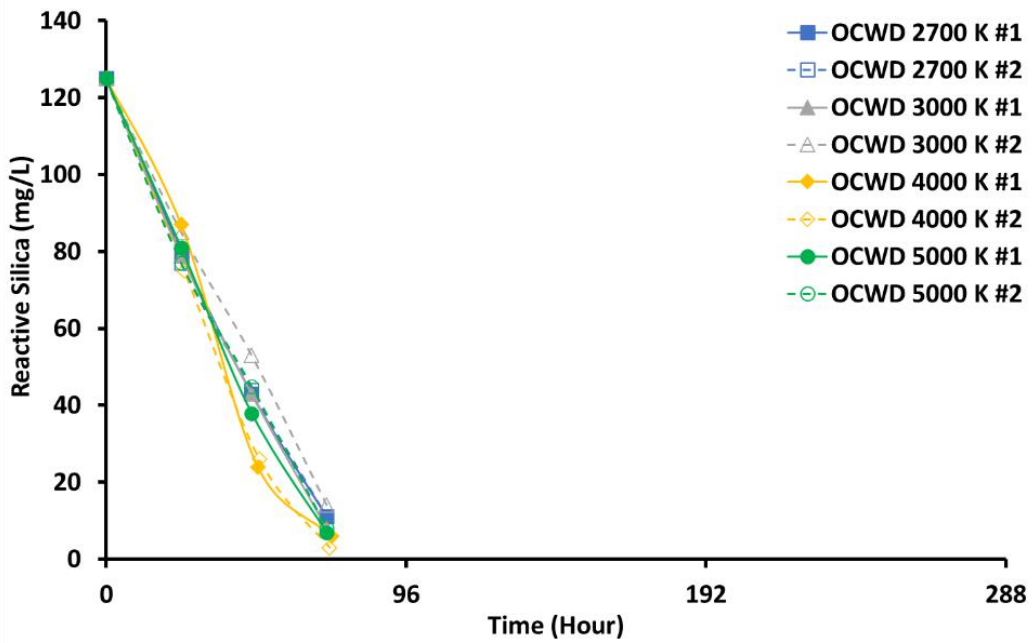


Figure 4-18. Light temperatures comparison in terms of silica uptake with OCWD GWRS ROC in the second cycle
(Temperature: 23 ± 1 °C, PAR: 200 ± 5 µmol m^{-2} s^{-1}, 10 W LED, 2,700, 3,000, 4,000, 5,000 K, initial biomass concentration: 0.127 g/L)

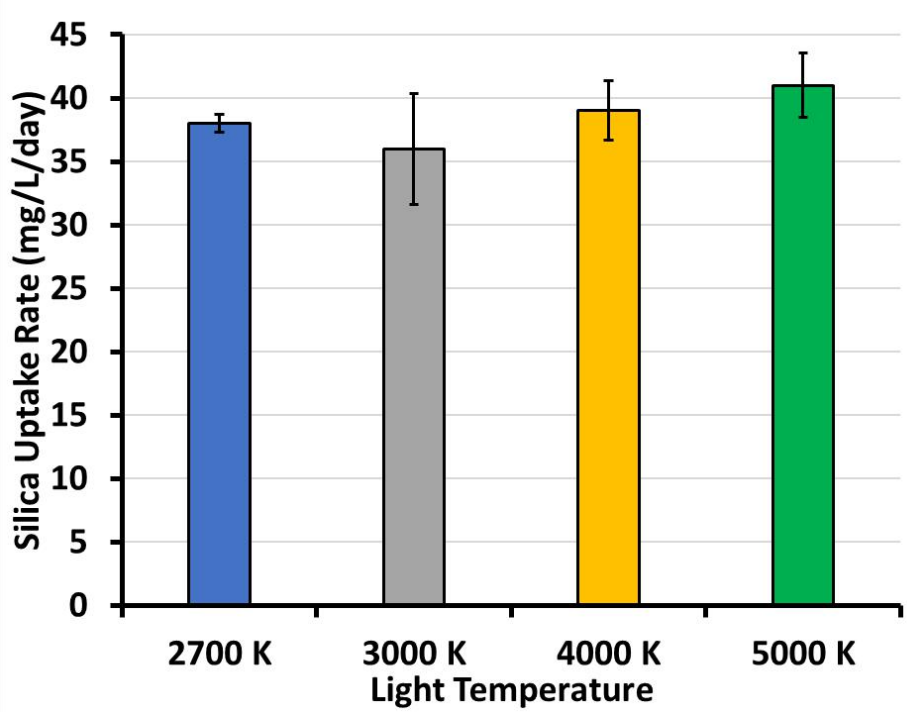


Figure 4-19. Average silica uptake rates of the two cycles in OCWD GWRS ROC
(See Figures 4-17 and 4-18 for the experimental conditions)

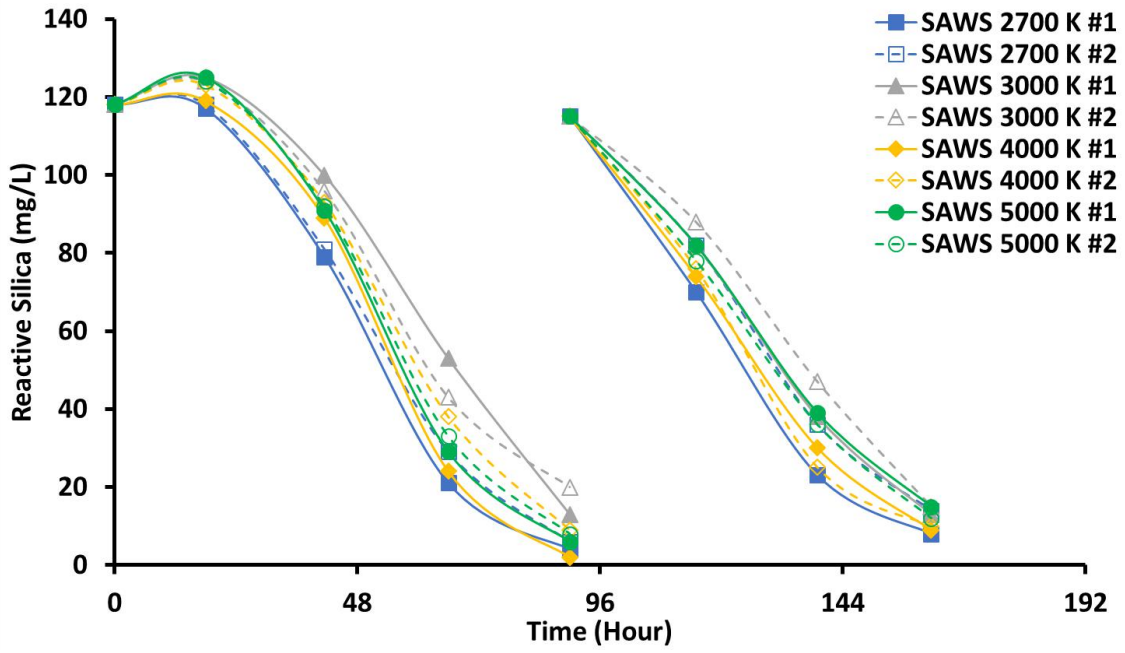


Figure 4-20. Two cycles of light temperatures comparison in terms of silica uptake with SAWS H2Oaks ROC
(Temperature: 23 ± 1 °C, PAR: 200 ± 5 µmol m^{-2} s^{-1}, 10 W LED, 2,700, 3,000, 4,000, 5,000 K, initial biomass concentration: 0.106 g/L)

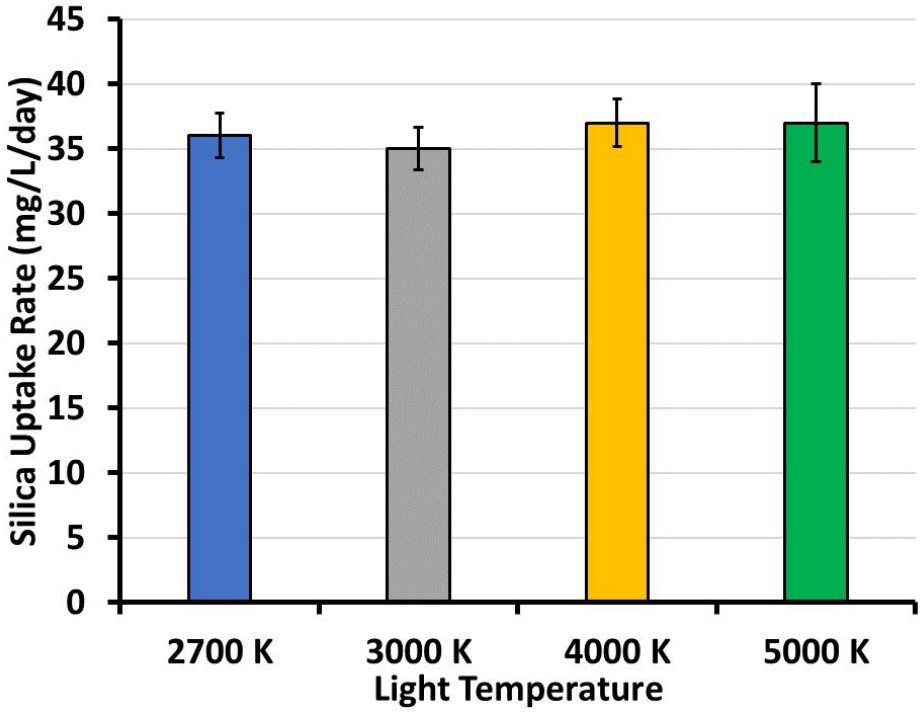


Figure 4-21. Average silica uptake rates of all cycles in SAWS H2Oaks ROC (See Figure 4-20 for the experimental conditions)

Light temperature, also called color temperature, was widely used in lighting industry nowadays. The four levels of light temperatures have slightly different colors which 2,700 and 3,000 K are soft white, 4,000 K is cool white, and 5,000 K is daylight. From experiences that low color temperature (warmer light) was often used in places like home to create a relaxing atmosphere, while high color temperature (cooler light) was preferred in offices or classrooms (Davis & Ginthner, 1990, p. 34). Figure 4-22 represents the light temperature scale of those four levels. Figure 4-23 shows the light spectrum graphs of four levels of light color temperatures. From this figure, 2,700 and 3,000 K were similar since their numerical values were very close. Based on the light spectrum, they have higher range of warm colors (red, orange, and yellow). For cooler colors like 4,000 and 5,000 K, there are higher photo flux density within the blue light

range than the other two levels. However, according to the results of silica uptake rates for the two ROCs, there was no significant impacts of light temperatures. Since 2,700 K bulbs are one of the commonly used ones, this type was used in the subsequent experiments. In the next experiment, it investigated more into details of specific pure colors if they will impact the silica uptake rates.

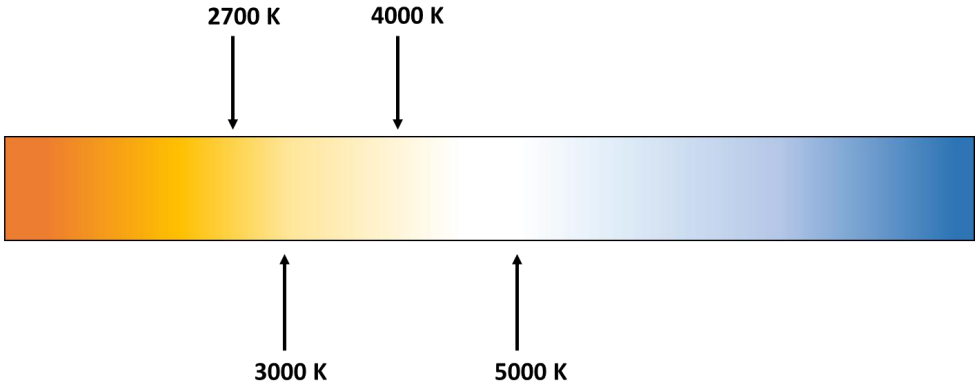


Figure 4-22. Light temperature scale

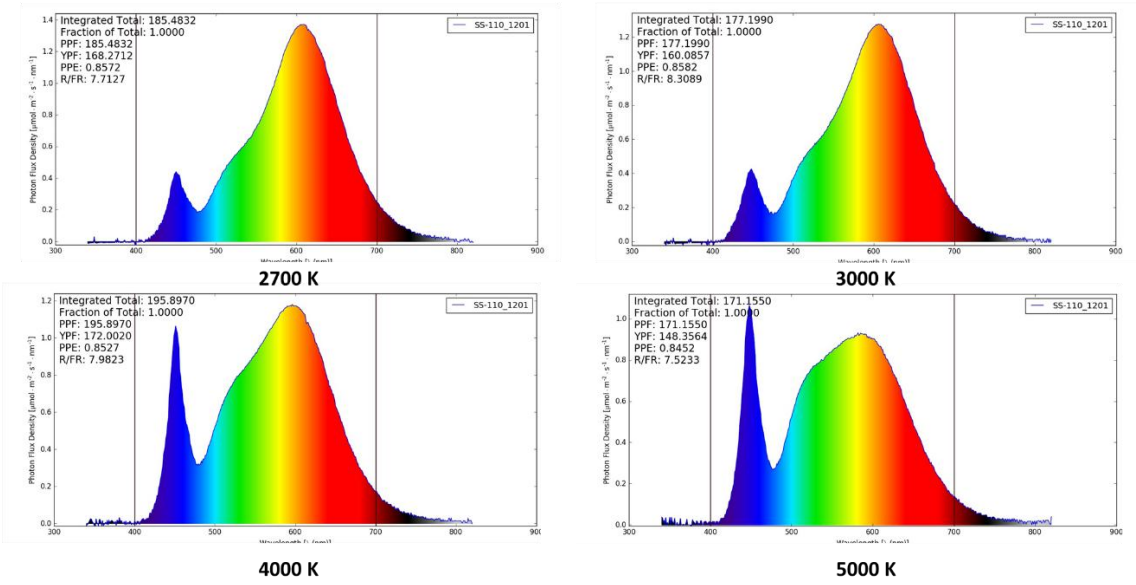


Figure 4-23. Light spectrum emitted by LED with different light temperatures

IV.II. II. LIGHT COLORS EXPERIMENT

Figures 4-24 and 4-25 show the impacts of different light colors in terms of silica uptake by the photobiological treatment in OCWD GWRS ROC. All colors had similar silica uptake rates, while the silica uptake was slightly faster with blue light than with others in the first and second cycles. The OCWD GWRS ROC has a yellowish background color, which may be one influence factor in the light color comparison experiments. Although the silica uptake rate under blue light (~28 mg/L/day) was slightly greater than others (~ 23 mg/L/day) in the OCWD GWRS ROC, it was not selected as the option since the output was six times weaker than other light colors. The bulbs used in this study had colored filters which reduced the photons. As shown in Figure 4-28, there were six bulbs were used to reach PAR equal to 50 μmol m^{-2} s^{-1} while others were using one bulb. Further research might be needed to investigate the impact of LEDs that emit blue light directly and silica uptake rate.

Figure 4-26 and 4-27 shows the experimental results for SAWS H2Oaks ROC comparing different light colors. While on the first cycle the silica uptake rates were within the range of 25 to 30 mg/L/day, in the second cycle, they were about 20 to 25 mg/L/day. The results indicate that there has no significant difference among the five colors.

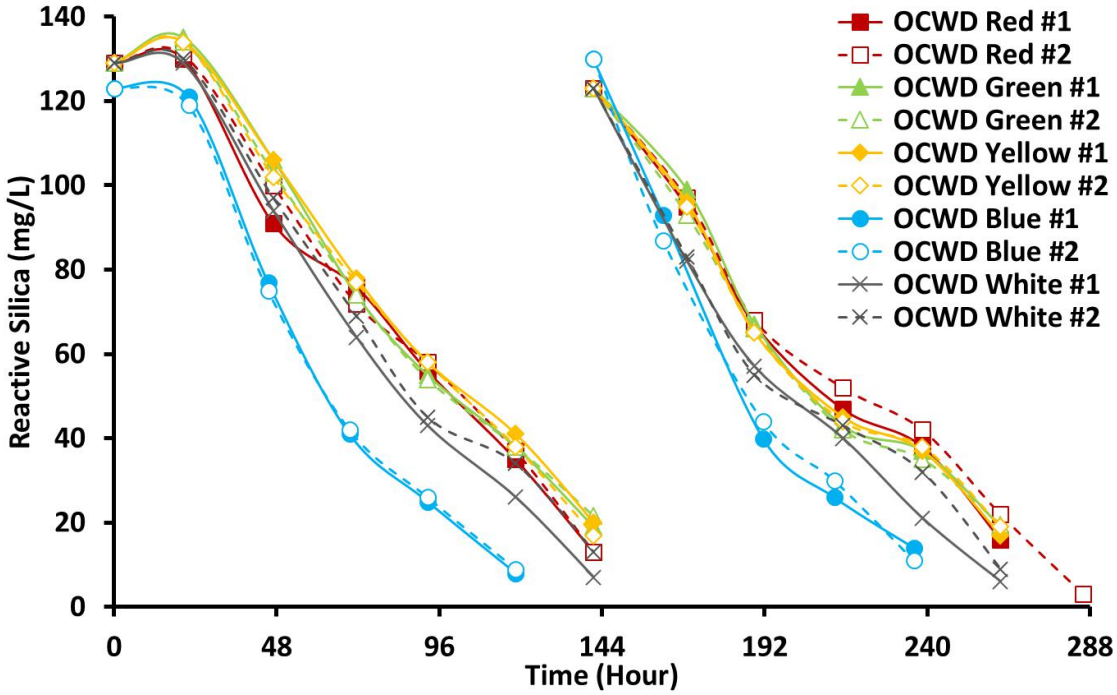


Figure 4-24. Silica uptake in OCWD GWRS ROC under incubation of five different light colors (Temperature: 21 ± 1 °C, PAR: 40 ~ 50 µmol m^{-2} s^{-1}, 8 W LED, red, green, yellow, blue, white (10W), initial biomass concentration: 0.343 g/L)

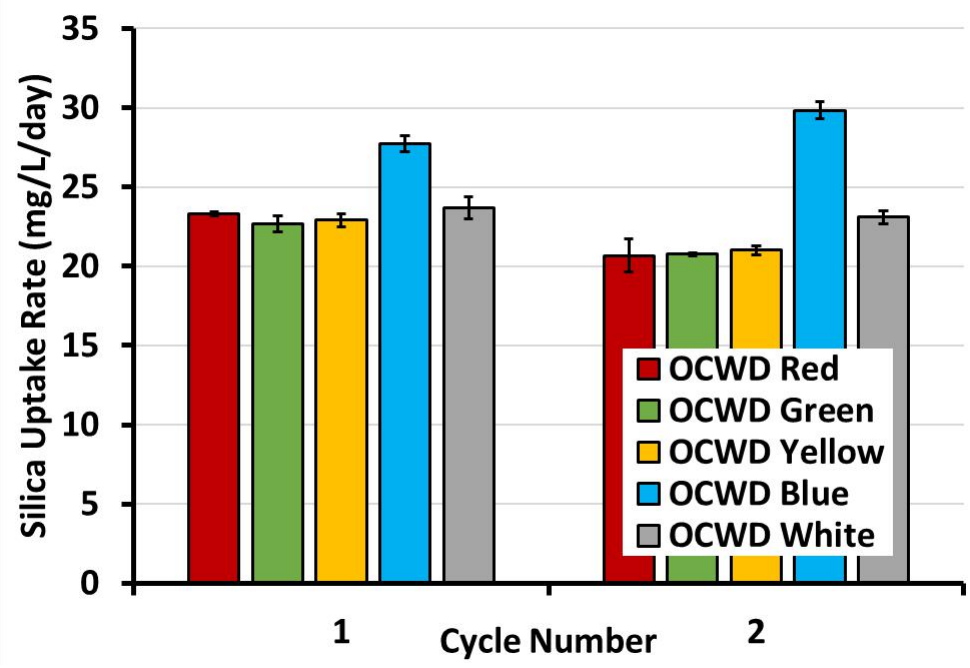


Figure 4-25. Silica uptake rates comparison for five colors in OCWD GWRS ROC (See Figure 4-24 for the experimental conditions)

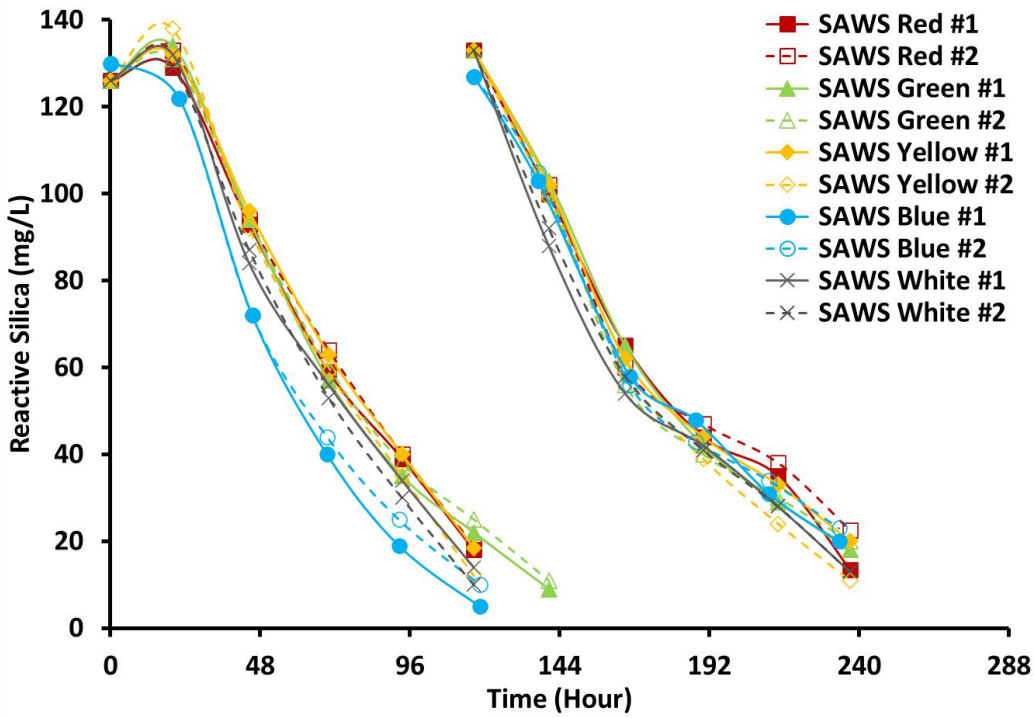


Figure 4-26. Silica uptake in SAWS H2Oaks ROC under incubation of five different light colors

(Temperature: 21 ± 1 °C, PAR: 40 ~ 50 µmol m^{-2} s^{-1}, 8 W LED, red, green, yellow, blue, white (10 W), initial biomass concentration: 0.335 g/L)

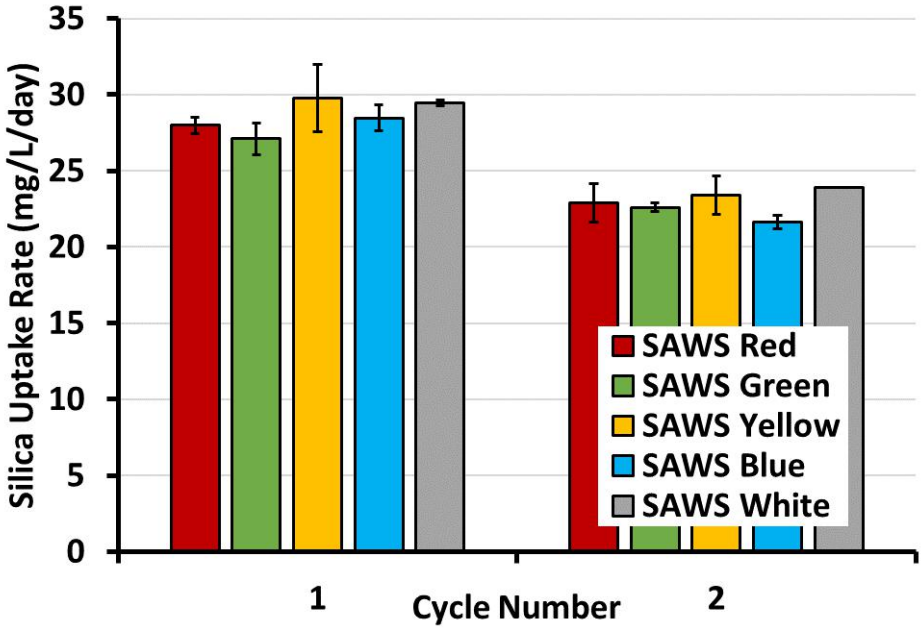


Figure 4-27. Silica uptake rates comparisons for five colors in SAWS H2Oaks ROC (See Figure 4-26 for the experimental conditions)

Figure 4-28 shows the light emission spectrums of different colored LED bulbs.

Warmer colors like red and yellow are within the wavelength range of 550 to 700 nm, while green and blue are less than 600 nm. Study shows that green algae grow better in blue and red light since the light harvesting pigments chlorophyll *a* and *b* are more sensitive to those colors (Singh & Singh, 2015). When algae like diatoms absorb energy, the blue light is more related to chlorophyll synthesis and chloroplast formation, while red light is more demanded in the growth processes such as increase cell size and photosynthesis mechanism (Yang, 2013). This was proved in a growth rate experiment in terms of the dissolved oxygen the algae produced (Harvenda et al., 2019a, p. 30005). However, in this study, there was no notable difference in silica uptake rates among these colors.

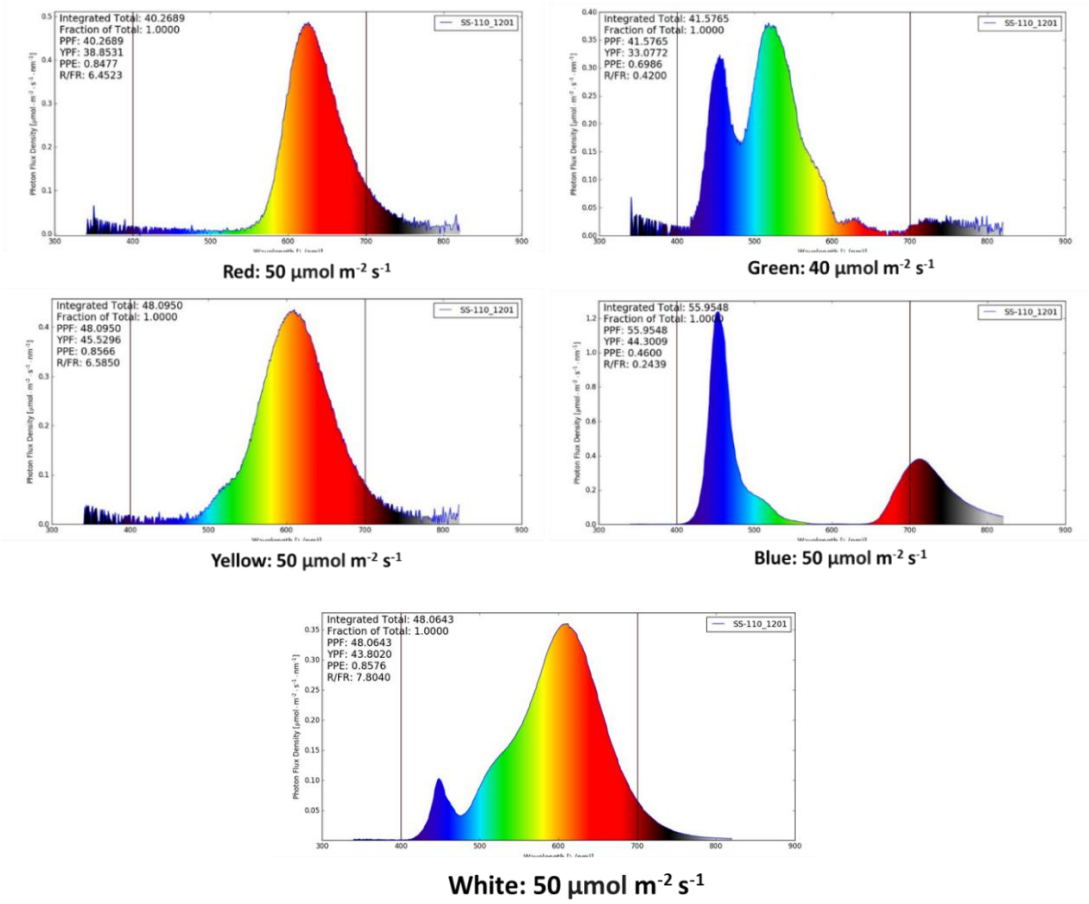


Figure 4-28. Light emission spectrums for five different light colors under PAR = 40 to 50 µmol m^{-2} s^{-1}

IV.II. III. LIGHT INTENSITIES EXPERIMENT

Figure 4-29 shows the impacts of different light intensities on the photobiological treatment in OCWD GWRS ROC. The silica uptake rate was higher with 310 and 510 µmol m^{-2} s^{-1} (46 to 50 mg/L/day) than 200 µmol m^{-2} s^{-1} (~40 mg/L/day) in the first two cycles, but almost the same at the third cycle. Situation was similar in SAWS H2Oaks ROC as shown in Figure 4-30, which has no significant differences in the silica uptake rate among 200, 310, and 510 µmol m^{-2} s^{-1}. Lower PARs like 50, 100 µmol m^{-2} s^{-1} are not recommended for the photobiological treatment of both OCWD GWRS and SAWS H2Oaks ROCs.

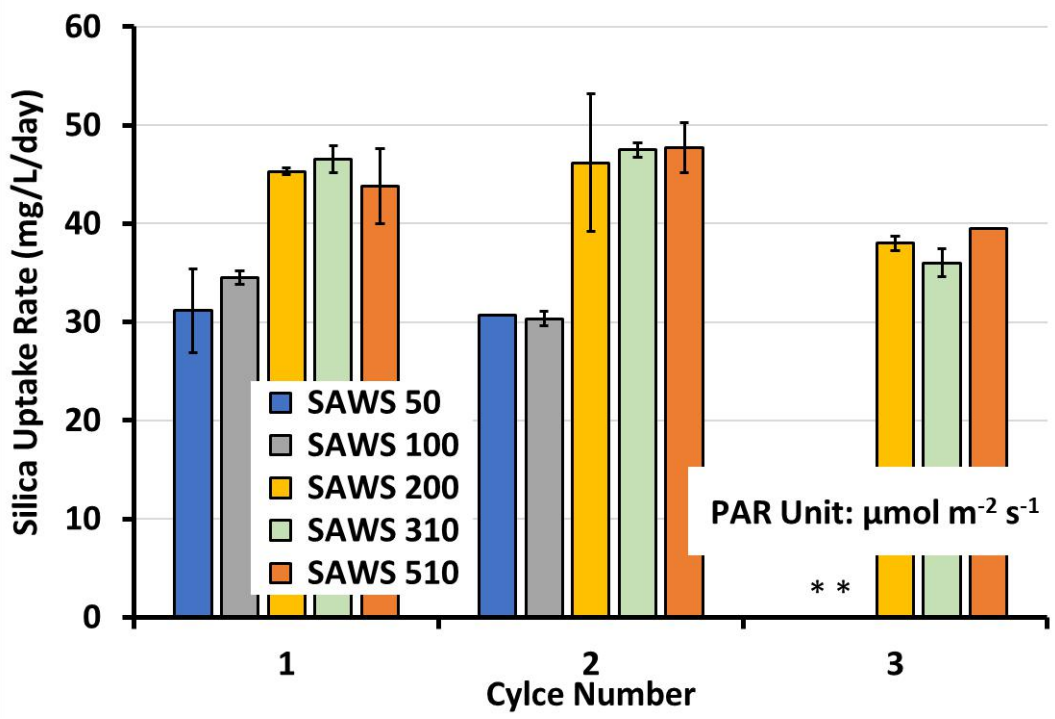


Figure 4-29. Three cycles of silica uptake rates comparison under different light intensities in OCWD GWRS ROC (*: N/A)
(Temperature: 23 ± 1 °C, PAR: 50, 100, 200, 310, 510 µmol m^{-2} s^{-1}, 10 W LED, 2,700 K, initial biomass concentration: 0.164 g/L)

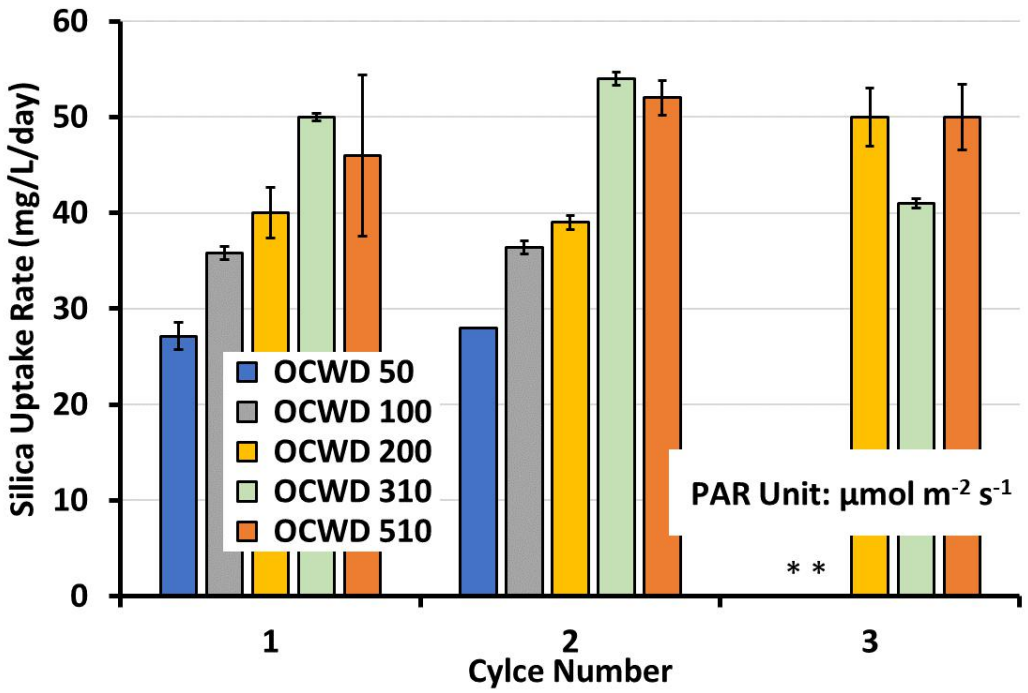


Figure 4-30. Three cycles of silica uptake rates comparison under different light intensities in SAWS H2Oaks ROC (*: N/A)
(Temperature: 23 ± 1 °C, PAR: 50, 100, 200, 310, 510 µmol m^{-2} s^{-1}, 10 W LED, 2,700 K, initial biomass concentration: 0.164 g/L)

Light was found to be an essential source for algae growth and photosynthetic activity. Algae such as diatom contain pigments like chlorophyll, which absorb light energy from the sun, and convert into chemical energy by photosynthesis (Singh & Singh, 2015, p. 432). During cell growth or production, diatom will take up silica since the cell wall is composed of silica. Therefore, when there was lower PAR, which means lower light energy, silica uptake rate will decrease due to slower growth. In the purpose of saving energy and reducing treatment cost, PAR equal to 200 µmol m^{-2} s^{-1} was used in the subsequent experiments.

IV.II. IV. INTERMITTENT & CONTINUOUS LIGHT EXPERIMENT

Figures 4-31 and 4-32 show the impacts of intermittent and continuous light on silica uptake rates in OCWD GWRS and SAWS H2Oaks ROCs. The intermittent light was set to turn on automatically at 12 PM and turn off at 12 AM while continuous light will provide 24-hour continuous illumination. Despite some lag period at the beginning, silica removal was completed in the first cycle for both ROCs.

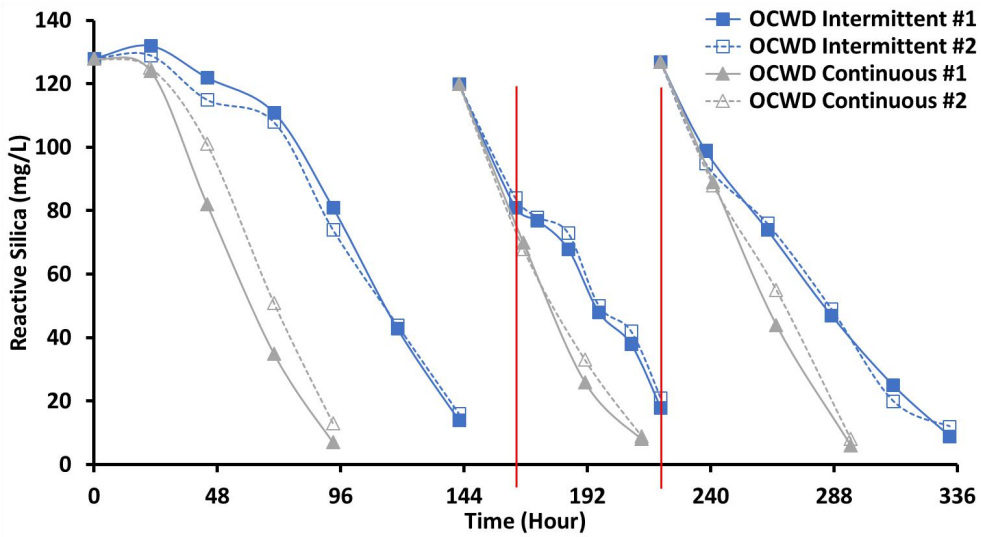


Figure 4-31. Intermittent and continuous light comparison in terms of silica uptake in OCWD GWRS ROC
(Temperature: 22 ± 1 °C, PAR: 200 ± 5 µmol m^{-2} s^{-1}, 10 W LED, 2,700 K, initial biomass concentration: 0.286 g/L)

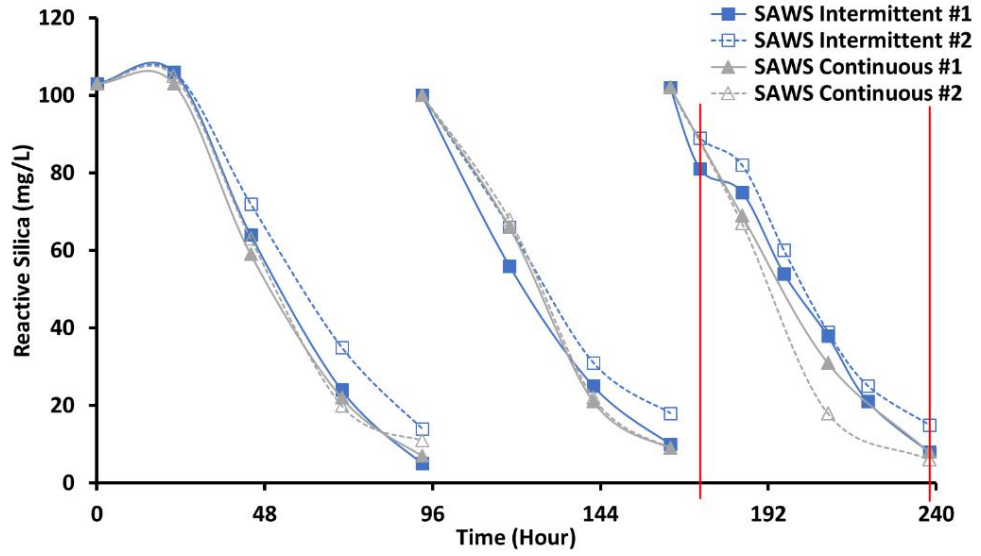


Figure 4-32. Intermittent and continuous light comparison in terms of silica uptake in SAWS H2Oaks ROC
(Temperature: 22 ± 1 °C, PAR: 200 ± 5 μmol m^{-2} s^{-1}, 10 W LED, 2,700 K, initial biomass concentration: 0.213 g/L)

To further investigate the difference of silica uptake rate between intermittent and continuous light, the silica concentrations were measure more frequently to see if silica uptake occurred during the dark period. A light controller was set to turn on the light at 7 AM and turn off at 7 PM during 173 hours to 221 hours (between the red lines in Figure 4-31 and 4-32). The results show that the silica uptake rates were similar for intermittent light conditions in both ROCs. It indicates that the intermittent light did not slow down the silica uptake, which is also proved in previous study (Ikehata et al,. 2018b). This is more apparent in the SAWS H2Oaks ROC (shown in Figure 4-33), since OCWD GWRS ROC has a yellowish background color which may have some impact on the silica uptake. Furthermore, the silica uptake rates indicate that taking up silica does not require continuous light. Intermittent light can be utilized in the full-scale photobiological treatment to save energy and reduce cost. Furthermore, this shows a huge implication in the photobiological treatment using sunlight as a light source since sun always provides intermittent light. The photoperiod, which is the period of time each day during algae receives illumination, is different for diverse algae species. With respect to increase cell growth or growth rate, some algae species prefer 16:8 h L:D, while others prefer 12: 12 h (Singh & Singh, 2015). Further research is needed to better understand the impact of photoperiod in terms of silica uptake rate by the diatoms.

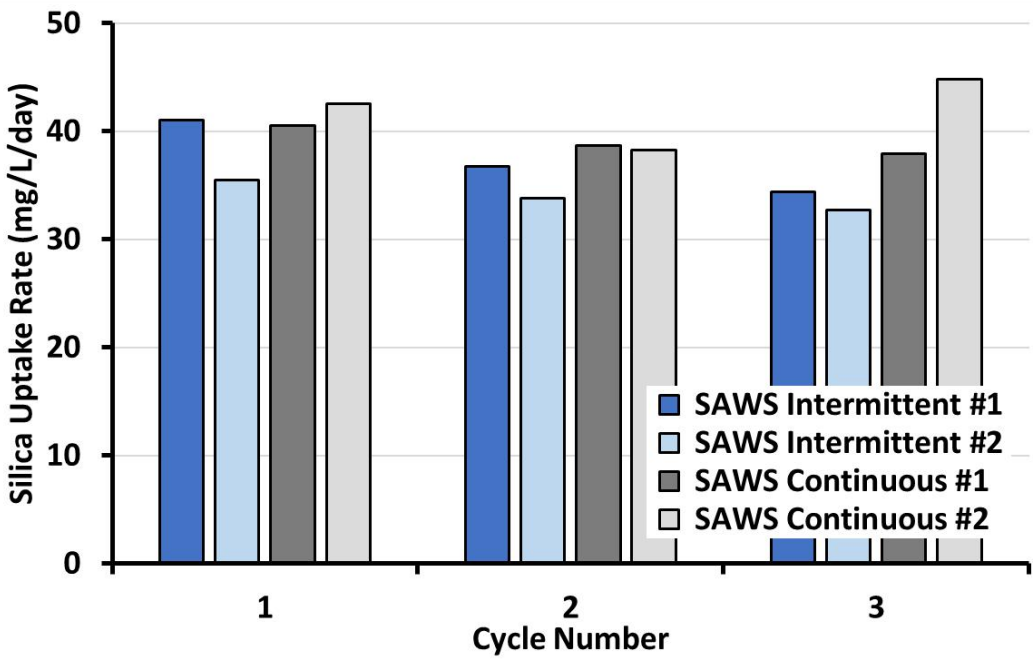


Figure 4-33. Silica uptake rates for intermittent and continuous light in SAWS H2Oaks ROC (See Figure 4-31 and 4-32 for the experimental conditions)

IV.II. V. INCUBATION TEMPERATURES EXPERIMENT

Figure 4-34 shows the impacts of different incubation temperatures by the photobiological treatment in OCWD GWRS ROC. It can be seen that 23 and 30 °C are the preferred incubation temperatures for silica uptake by the photobiological treatment. Although the silica uptake was slow at 10 °C, the silica removal reached >85% after 192 hours. However, the photobiological treatment did not work at 40 °C and silica concentration slightly increased in both ROCs. The high temperature might induced silica release from intracellular pool of soluble silica (Ikehata et al., 2018b). Figure 4-35 shows the silica up take rates in the OCWD GWRS ROC. The silica uptake rate was slightly higher at 23 °C than at 30 °C.

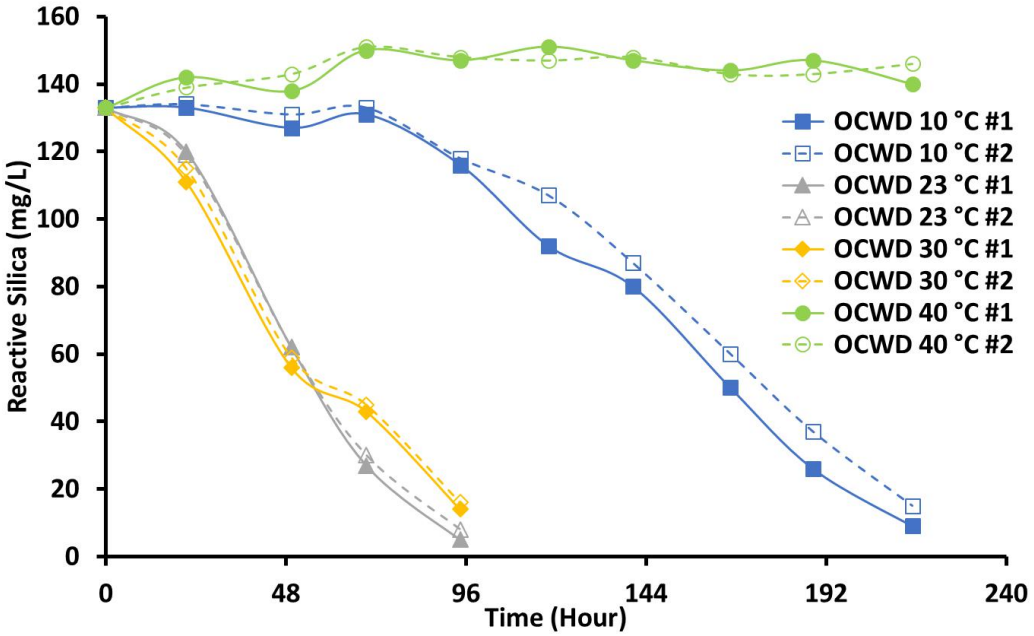


Figure 4-34. Silica concentration for four different incubation temperatures in OCWD GWRS ROC
(Temperature: 10, 23, 30, 40 °C, PAR: 200 ± 5 µmol m^{-2} s^{-1}, 10 W LED, 2,700 K, initial biomass concentration: 0.284 g/L)

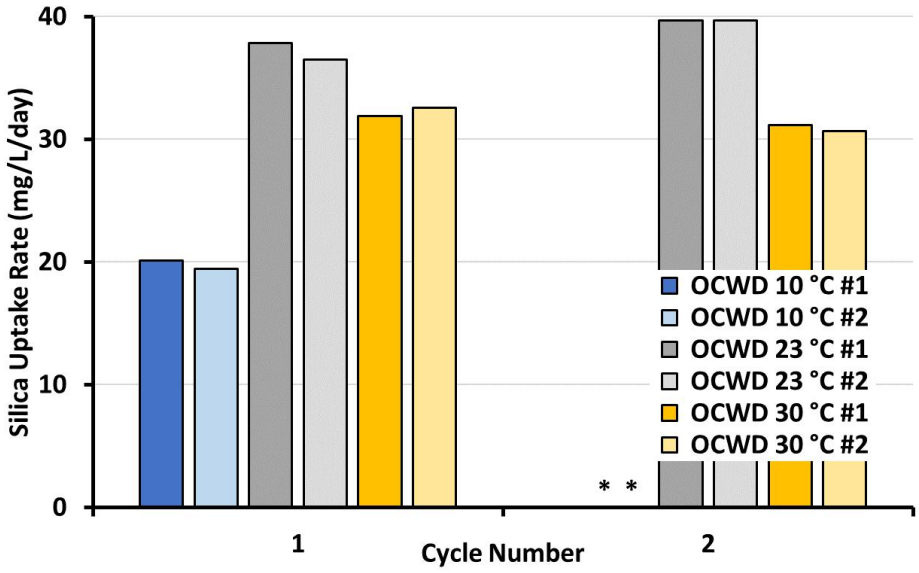


Figure 4-35. Silica uptake rates under four levels of incubation temperatures in OCWD GWRS ROC (*: N\A)
(See Figure 4-34 for the experimental conditions)

The results were similar in the SAWS H2Oaks ROC, as shown in Figures 4-36 and 4-37. The photobiological treatment under incubation temperatures of 10 °C was very slow, and 40 °C was too high.

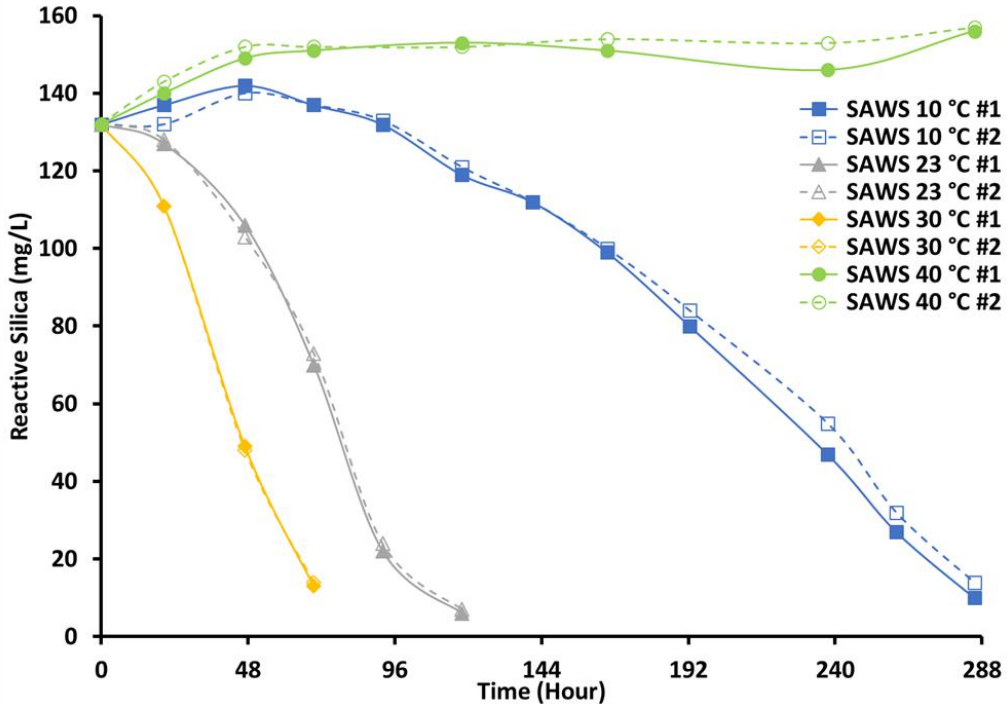


Figure 4-36. Silica concentration for four different incubation temperatures in SAWS H2Oaks ROC
(Temperature: 10, 23, 30, 40 °C, PAR: 200 ± 5 µmol m^{-2} s^{-1}, 10 W LED, 2,700 K, initial biomass concentration: 0.288 g/L)

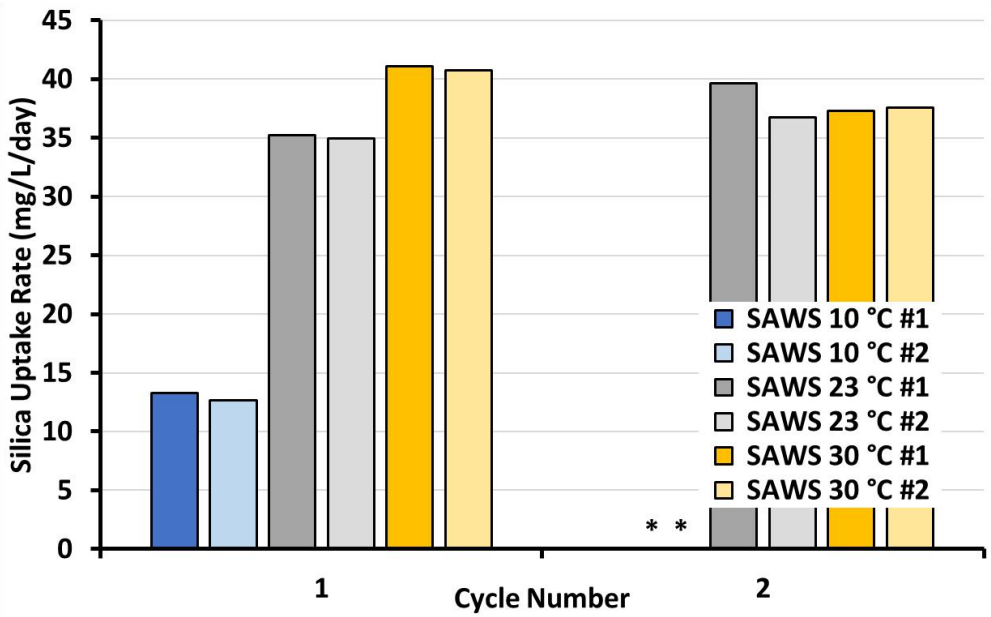


Figure 4-37. Silica uptake rates under four levels of incubation temperatures in SAWS H2Oaks ROC (*: N\A)
(See Figure 4-36 for the experimental conditions)

In previous study, it showed that silica uptake slowed down and slightly increased during the day when water temperature reached around 40 °C (Ikehata et al., 2018b). Temperature is an important factor that was known to affect the growth of algae like diatoms. It strongly influences the cellular metabolism such as uptake of nutrients or carbon dioxide, and growth rate of algae (Singh & Singh, 2015). Although I did not investigate the relationship of temperature and growth rate directly, the experimental results proved that the temperature will also impact silica uptake by the diatoms. Further studies may need to find the temperature for achieving optimum silica uptake rate. Figure 4-38 shows the photomicrograph of diatom cells incubated at 23 and 40 °C. While the diatoms cells incubated at 23 °C were green, those ones incubated at 40 °C looked like

bleached, and there were no green pigments in them. During the experiment, the color of biomass changed from green to white, which means they died at such a high incubation temperature.

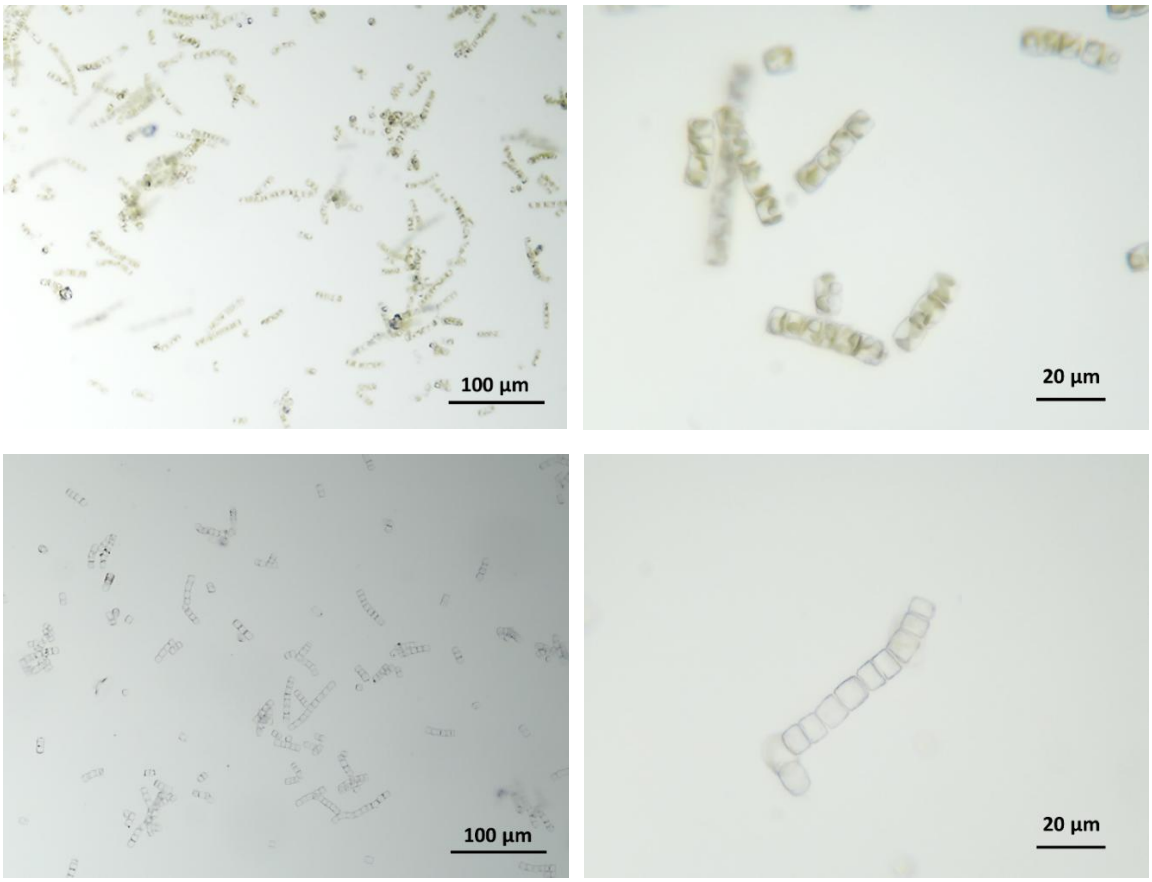


Figure 4-38. Photomicrography of diatoms for incubations at 23 (top graphs) and 40 °C (bottom graphs)

IV.III. TREATABILITY STUDY

The objective of this series experiments was to test the treatability of the photobiological treatment and understand the difference among these ROCs. The ROCs used were from Hamby Water Purification Facility, Kay Bailey Hutchison Water Treatment Plant, OCWD GWRS CCRO (CCRO: closed-circuit RO), and West Basin Municipal Water District.

IV.III. I. ABILENE HAMBY WRF & EL PASO KBHDP ROCS

Figure 4-39 shows the silica uptake by the photobiological treatment in both Hamby WRF and KBHDP ROCs. For both ROCs, they were able to finish two cycles of silica uptake, all starting from different initial silica concentrations. Table 4-4 shows the nutrients concentration for raw and after added F/2 Algae Food in KBHDP. Supplementary nutrients of 4 mg/L of orthophosphate and 10 mg/L of nitrate-N were added to the KBHDP ROC at the beginning of each cycle, which was previously proved to support the completion of three cycles in SAWS H2Oaks ROC.

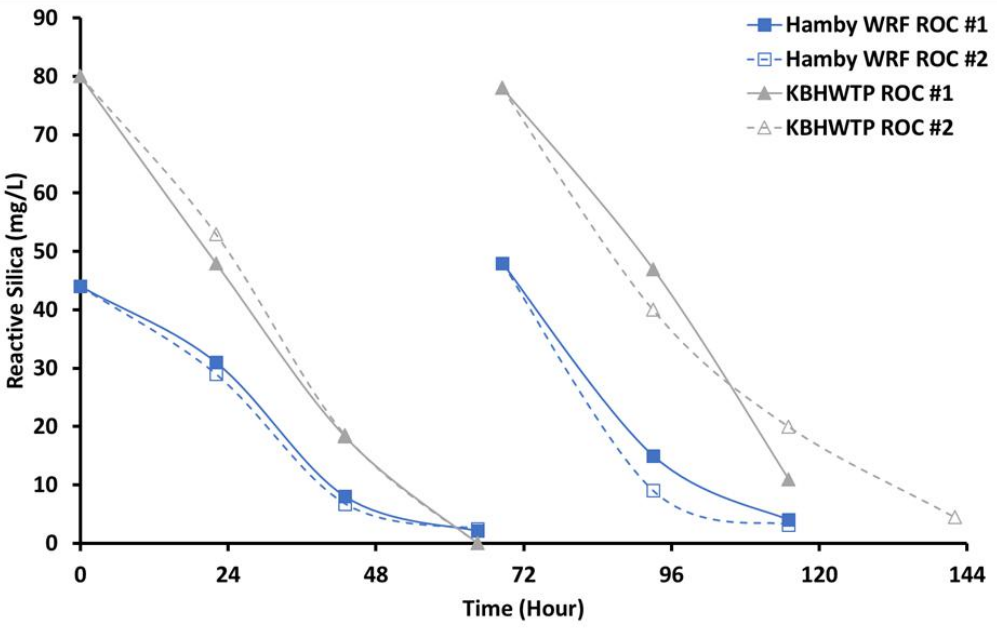


Figure 4-39. Silica concentration by the photobiological treatment in Hamby WRF and KBHDP ROCs
(Temperature: 24 ± 0.5 °C, PAR: 200 ± 5 μmol m^{-2} s^{-1}, 10 W LED, 2,700 K, initial biomass concentration: 0.375 g/L)

Table 4-4. Raw and with algae food nutrients concentration for KBHDP

Parameters	Raw	+ AF
Nitrate (mg/L as N)	<0.23	10
Ammonia (mg/L as N)	<0.4	<0.4
Orthophosphate(mg/L as PO_4^{3-})	0.3	4

IV.III. II. OCWD CCRO & WBMWD ECLWRF ROCS

Figure 4-40 shows the silica uptake of the treatability study in both WBMWD and OCWD CCRO ROCs. Although OCWD CCRO ROC contained a high concentration of nitrate (~100 mg/L as N), three cycles of photobiological treatment were completed. For WBMWD ROC, there was a long lag time which silica concentration decreased and then raised. In previous studies, it was found that >24 mg/L of ammonia-N concentration was inhibitory for silica uptake (Kulkarni et al., 2019). The toxicity of ammonia-N in algae growth has been know (Provasoli, 1958; Collos & Harrison, 2014), but a low level (<10 mg/L) of ammonia-N was the preferred nitrogen source in the research (Ikehata et al., 2018a). The high concentration of ammonia-N (~310 mg/L) in WBMWD ROC inhibited silica uptake by the photobiological treatment.

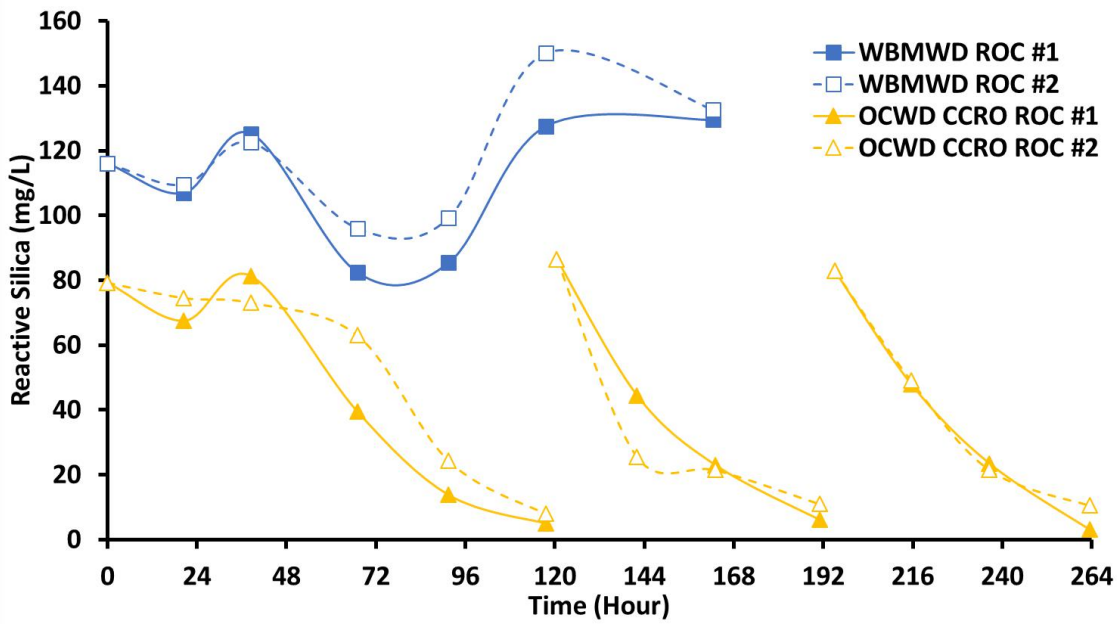


Figure 4-40. Silica uptake by the photobiological treatment in WBMWD and OCWD CCRO ROCs

(Temperature: 24 ± 0.5 °C, PAR: 200 ± 5 µmol m^{-2} s^{-1}, 10 W LED, 2,700 K, initial biomass concentration: 0.101 g/L)

IV.IV. OUTDOOR AND *N*-NITROSAMINE REMOVAL INVESTIGATION EXPERIMENT

Figure 4-41 shows the silica uptake by the photobiological treatment for the indoor experiment with LED light. The silica uptake rate was 57 mg/L/day in the first cycle and increased to 68 mg/L/day in the second cycle, which reached >85% within 48 hours. The differences between this LED experiment and previous ones were the reactor and ROC volume. The jar used in this experiment has larger/spreading surface area which might helped diatom growth. Instead of 100 mL ROC, there was 400 mL OCWD GWRS ROC in each jar, and initial biomass concentration was similar as previous experiments. The final biomass concentration was a lot more (~50 times) than previous ones, with comparable incubation time (in days). It was speculated that the larger surface area and higher initial biomass concentration could promote the faster silica uptake.

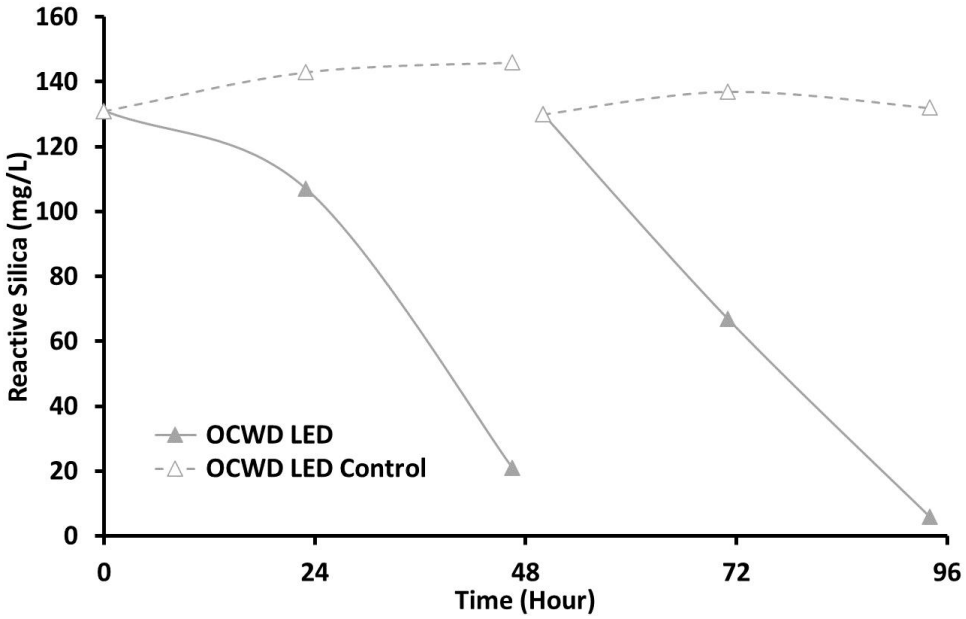


Figure 4-41. Silica uptake for indoor experiment under LED light with OCWD GWRS ROC (Temperature: 24 ± 0.5 °C, PAR: 200 ± 5 µmol m^{-2} s^{-1}, 10 W LED, 2,700 K, initial biomass concentration: 0.185 g/L)

Figure 4-42 shows the silica uptake with sunlight in the first outdoor experiment. There was no silica uptake for around five days in the first cycle (before the red line). The 500-mL jars had transparent lids made by Plexiglas sheet, which gave ~93% and ~16% transmittance rate for PAR and UV, respectively. Based on the temperature graph in Figure 4-43, the temperature for the first cycle was fluctuating from around 7 to 35 °C, which should not be a problem for silica uptake based on the results from previous experiments. Therefore, the possible reason may be the high level (up to 6.9 W m^{-2}) of UV (Table 3-7).

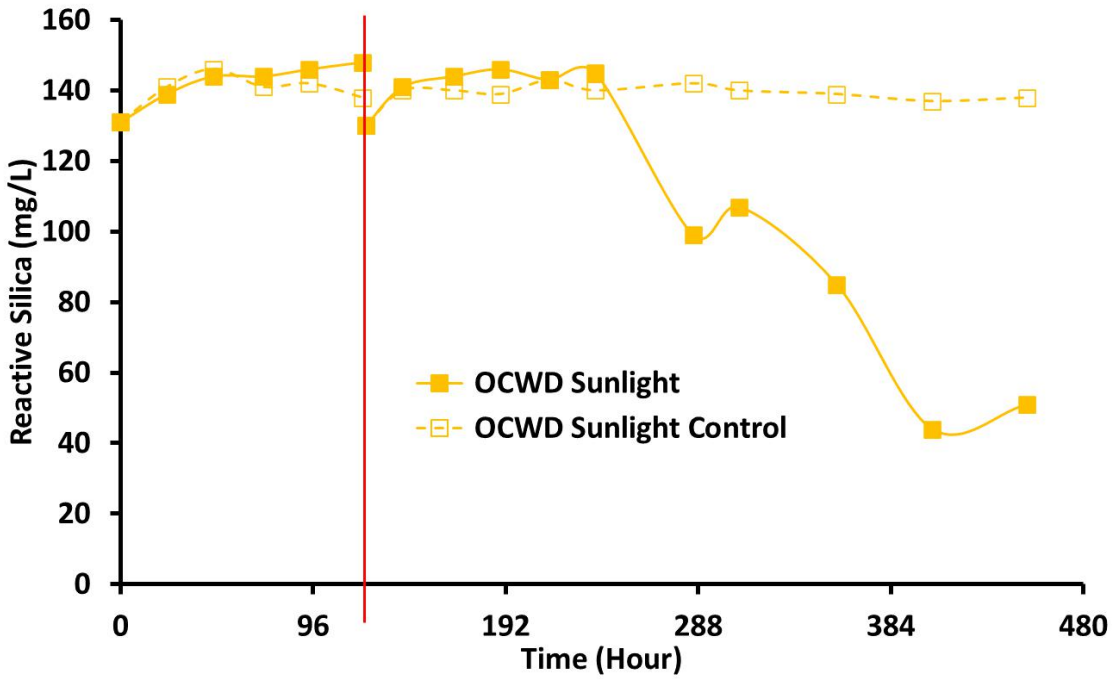


Figure 4-42. Silica concentration for sunlight outdoor experiment (1st run) with OCWD GWRS ROC
(Temperature: 20 ± 7 °C, PAR: 400 ~ 1,800 µmol m^{-2} s^{-1} (with Plexiglas lid), 30 ~ 355 µmol m^{-2} s^{-1} (with white lid), Sunlight, initial biomass concentration: 0.185 g/L, added biomass on Day 5: ~ 0.19 g/L)

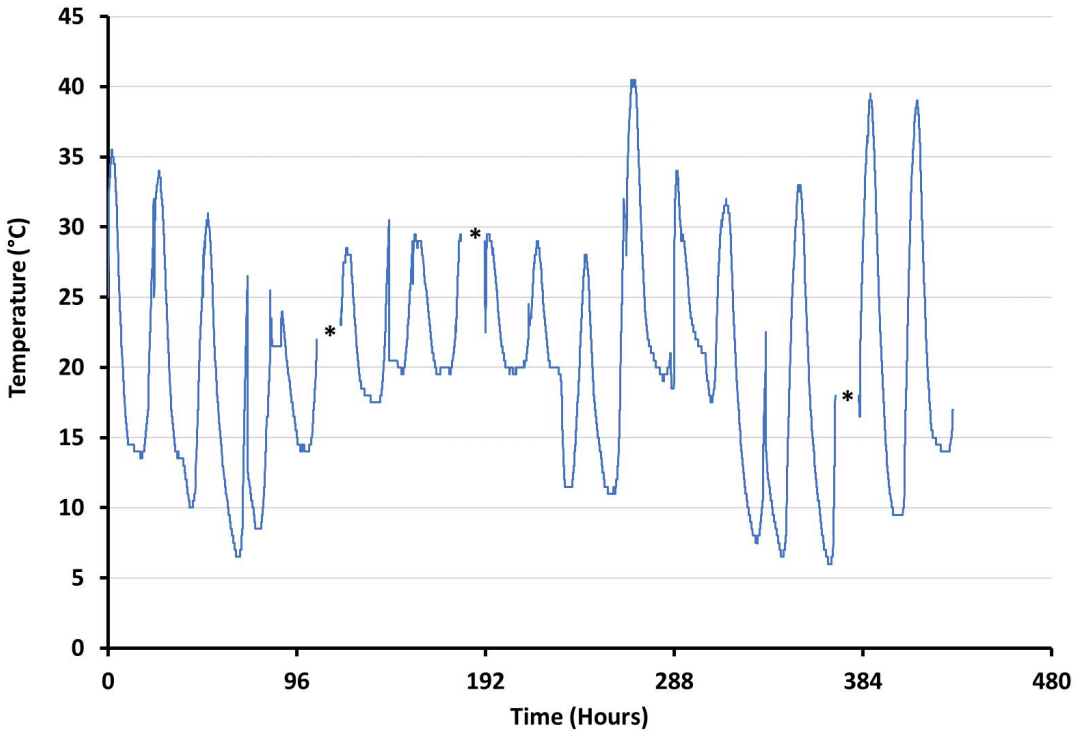


Figure 4-43. Temperature data for sunlight outdoor experiment with OCWD GWRS ROC, *: data missing
(See Figure 4-42 for the experimental conditions)

Figure 4-44 shows the photomicrograph of diatoms cells after the first cycle. Although the diatom cells appeared to be dead with sunlight, their appearance was clearly different from the dead cells observed during the incubation temperature experiment (Figure 4-38). Unlike the bleached cells, those diatoms were aggregated with some green chloroplast, but there was no silica uptake. This is likely due to the mechanisms of diatom inactivation. In a research studied the inactivation of a cyanobacteria using UV-radiation indicated that a UV dose of 75 mW s cm^{-2} was lethal and 37 mW s cm^{-2} prevented the growth of the cyanobacteria for around 7 days. Due to this characteristics, UV lamps or reactors are often used in eutrophic lakes to control algae growth, which is a good alternative than adding harmful chemicals such as copper sulfate to the water (Zamir Bin Alam et al., 2001).

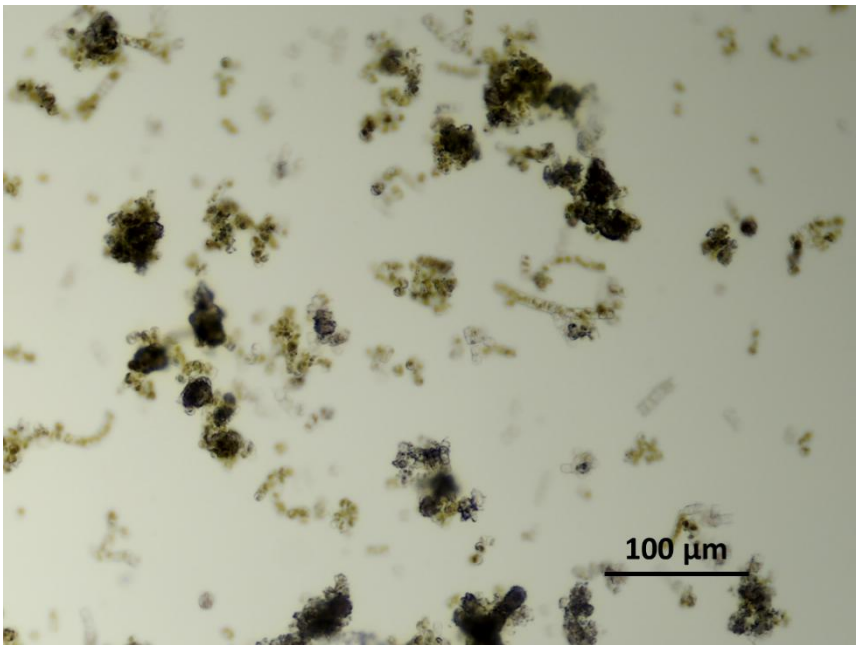


Figure 4-44. Photomicrograph of diatoms cells after the 1st cycle

After 5 days, the lids were replaced with white lids (Figure 4-45), which gave them ~15.5% transmittance for PAR and ~2% transmittance for UV (see Table 3-7). However, it did not show decreasing silica uptake trend for 3 days. It was assumed that all the diatoms were dying/exhausted. Therefore, 5 mL fresh biomass mixed solution was added to the jar with diatom. After another short lag period, silica concentration started to decrease. There were two points that shows increased silica concentration on Figure 4-42. It might be due to the high temperatures in those two days which reached 41 ºC. This was also proved in my previous incubation temperatures comparison experiment which indicated that silica uptake did not happen in high temperature like 40 ºC. The average temperature data measured by temperature loggers, daily PAR and UV, and weather data during the outdoor experiment (1st run) were presented in Table 3-6, 3-7, and 3-8.

Figure 4-45. The experimental settings with white lids of the second cycle in outdoor experiment (See Figure 4-42 for the experimental conditions)

Figures 4-46 and 4-47 below shows the NDMA and NMOR concentrations during the 1st run outdoor experiment with OCWD GWRS ROC. Comparing to the silica uptake in Figure 4-42, there was no NDMA removal in LED light since it has no UV. Although in previous studies, it showed that 67% of NDMA was removed by LED (Ikehata et al., 2018b). For the sunlight control jars (no diatom), both NDMA and NMOR concentrations decreased to <6 ng/L at the end of each cycle. It confirmed that NDMA can be directly photolyzed by solar UV radiation (Stefan & Bolton, 2002). For the sunlight jar (with diatom), the first cycle exhibited no silica uptake and NDMA removal. In the second cycle, NDMA and NMOR concentrations decreased as silica uptake continued. Further research may be needed to investigate the increase of NDMA during the photobiological treatment (when no silica uptake).

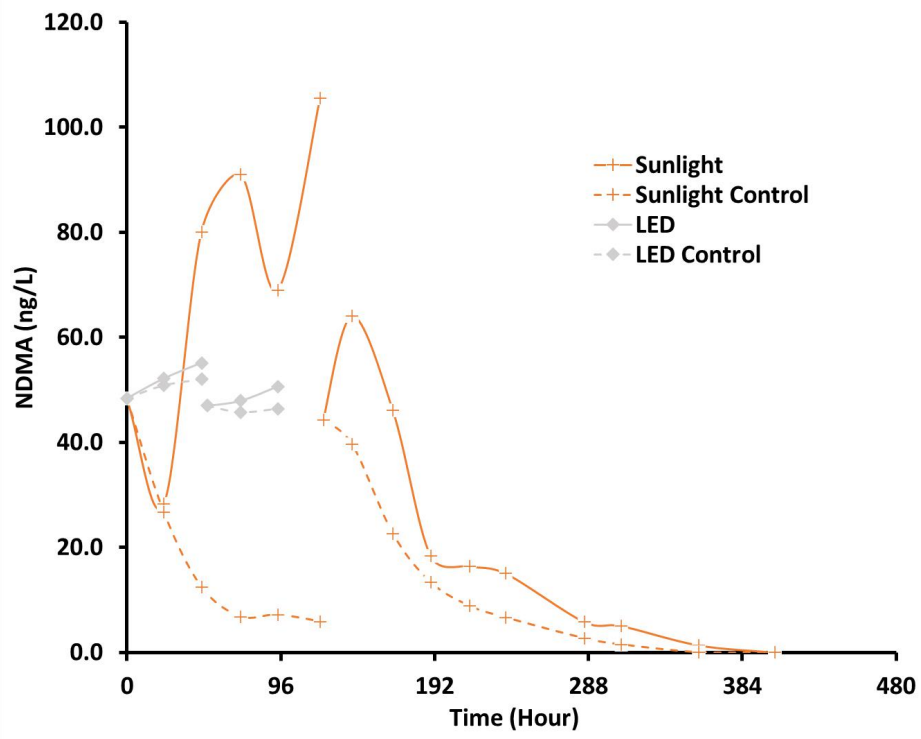


Figure 4-46. NDMA concentration for outdoor experiment (1st run)
(See Figure 4-42 for the experimental conditions)

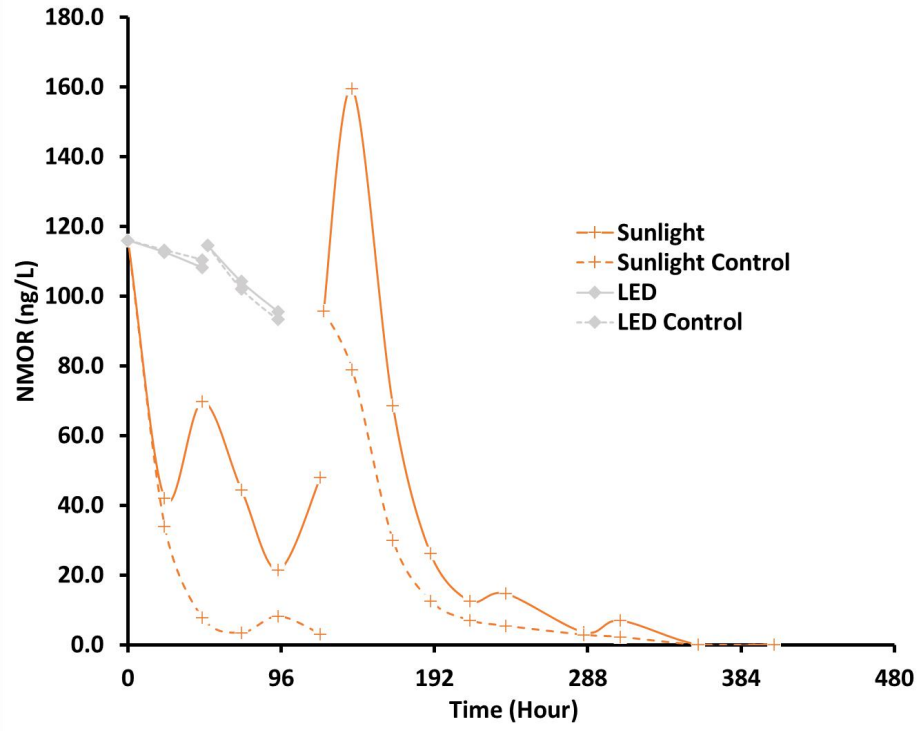


Figure 4-47. NMOR concentration for outdoor experiment (1st run)
(See Figure 4-42 for the experimental conditions)

Based on the experimental results of the last experiment and previous studies, the temperature and strong UV may be the reasons of no silica removal in the outdoor experiments (Ikehata et al., 2018b). Therefore, a follow-up experiment with sunlight was conducted. Later, the two jars were moved to another place on the patio (Figure 3-13) which has less sunlight, shown in Figure 4-48. Also, a reflecting sheet was placed under the jars to insulate the ground and reactors. However, as shown in Figure 4-49, there was no silica uptake for 72 hours. Table 3-9 indicates that the temperatures were too high in the three days, with highest of 42.5 °C. The temperature graph shown in Figure 4-50 indicates that there were three sections that > 40 °C.

Figure 4-48. The outdoor experiment with reflecting sheet
(Temperature: 28 ± 8.5 °C, PAR: 213 ~ 624 μmol m^{-2} s^{-1}, Sunlight, initial biomass concentration: 0.194 g/L)

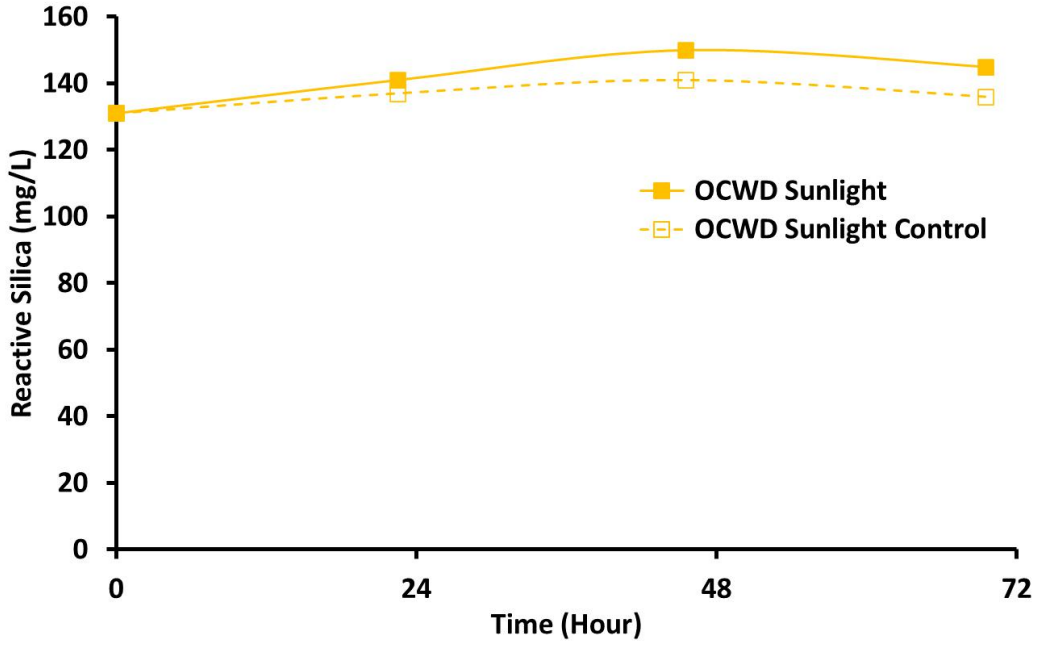


Figure 4-49. Silica concentration for sunlight outdoor experiment (2nd run) with OCWD GWRS ROC
(Temperature: 28 ± 8.5 °C, PAR: 213 ~ 624 µmol m^{-2} s^{-1}, Sunlight, initial biomass concentration: 0.194 g/L)

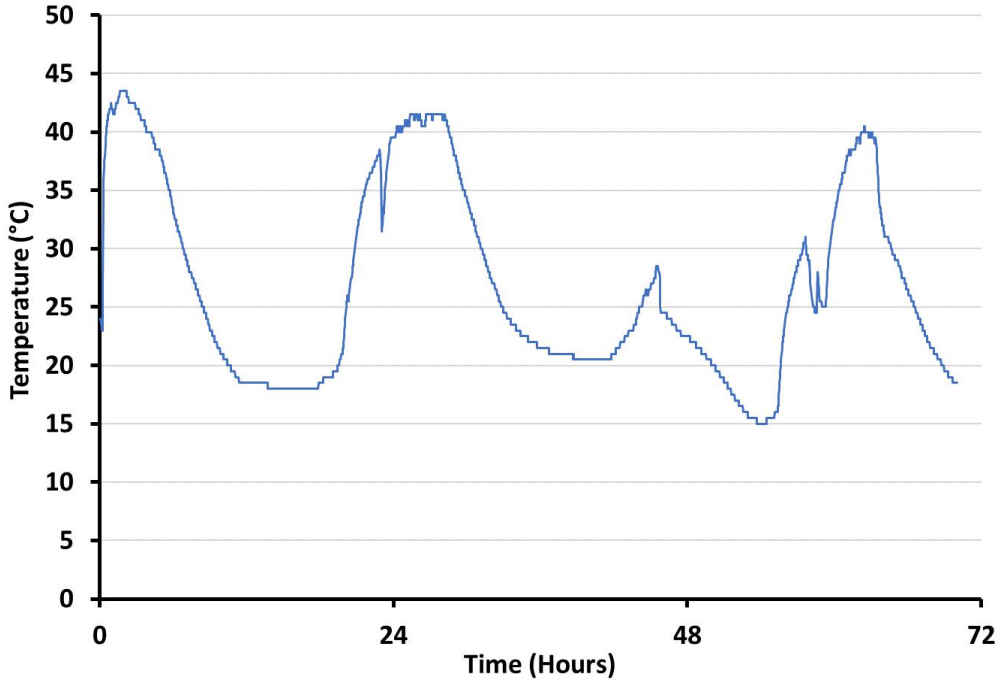


Figure 4-50. Temperature data for sunlight outdoor experiment (2nd run) with OCWD GWRS ROC
(See Figures 4-48 and 4-49 for the experimental conditions)

The photomicrograph for this experiment is shown in Figure 4-51. Compared to the diatoms under constant 40 °C (Figure 4-38), they look similar and many of the cells were bleached and killed by the high temperature. These results shows that silica uptake will not happen under high incubation temperature. Figure 4-52 shows the NDMA and NMOR concentrations after the photobiological treatment. As all others went down to <2.5 ng/L, there was no significant NDMA reduction in sunlight jar (with diatom). The reasons for that are still unknown since NDMA should be degraded by UV. But when there was no silica uptake, NDMA removal was insignificant. Further studies are needed to investigate the relation between diatom, silica uptake and NDMA removal.

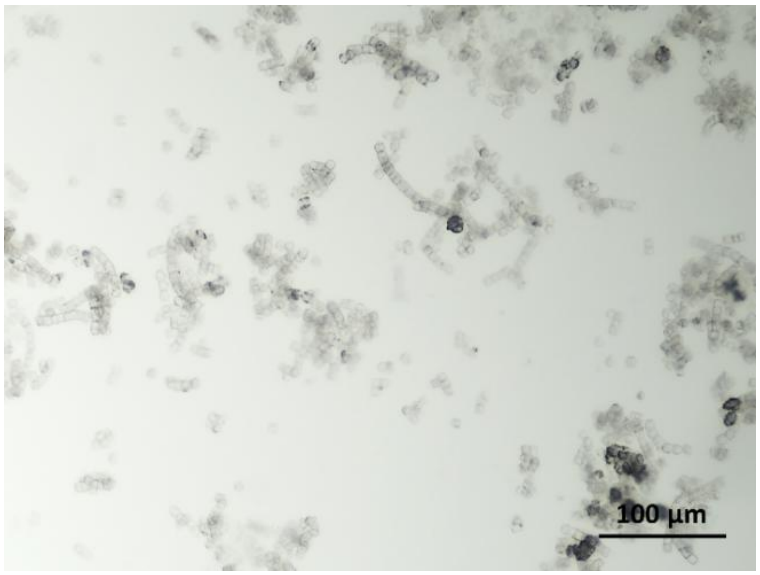


Figure 4-51. Photomicrograph comparison between diatoms under 17.8 ~ 42.5 °C

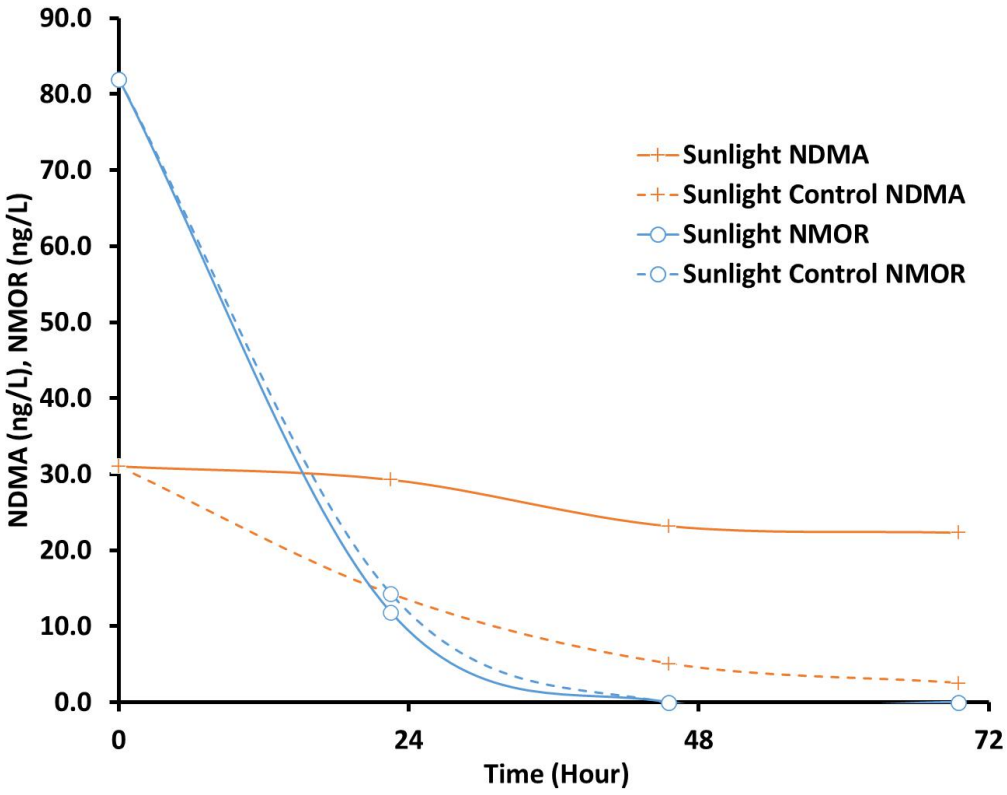


Figure 4-52. NDMA and NMOR concentrations for the outdoor experiment (2nd run) with OCWD GWRS ROC
(See Figures 4-48 and 4-49 for the experimental conditions)

The experimental plan was reconsidered later and then the jars were put near the fence of patio (Figure 3-13), so there will be <1 hour direct sunlight on the jars (UV: 0.1 ~ 0.9 W m^{-2}), and the reflecting sheet covered the whole tile on the ground to control increasing temperature by sunlight. Figure 4-54 shows the silica uptake by the photobiological treatment under sunlight. Comparing with the temperature graph shown in Figure 4-55, the first cycle had lower temperatures during nights, which also had slower silica uptake rate. At the second cycle, silica uptake rate increased with raised average temperature. The temperature in most time of the first two cycles were below 40 °C, which reached >75% silica uptake for both cycles. Then the temperature raised in

the daytime with highest of >45 °C on Day 5 of the third cycle. The small increase of silica concentration at that time cycle is likely due to the high temperature of that day.

Figure 4-53. New outdoor experiment setup near the fence
(Temperature: 21 ± 5 °C, PAR: 13 ~ 606 µmol m^{-2} s^{-1}, Sunlight, initial biomass concentration: 0.21 g/L)

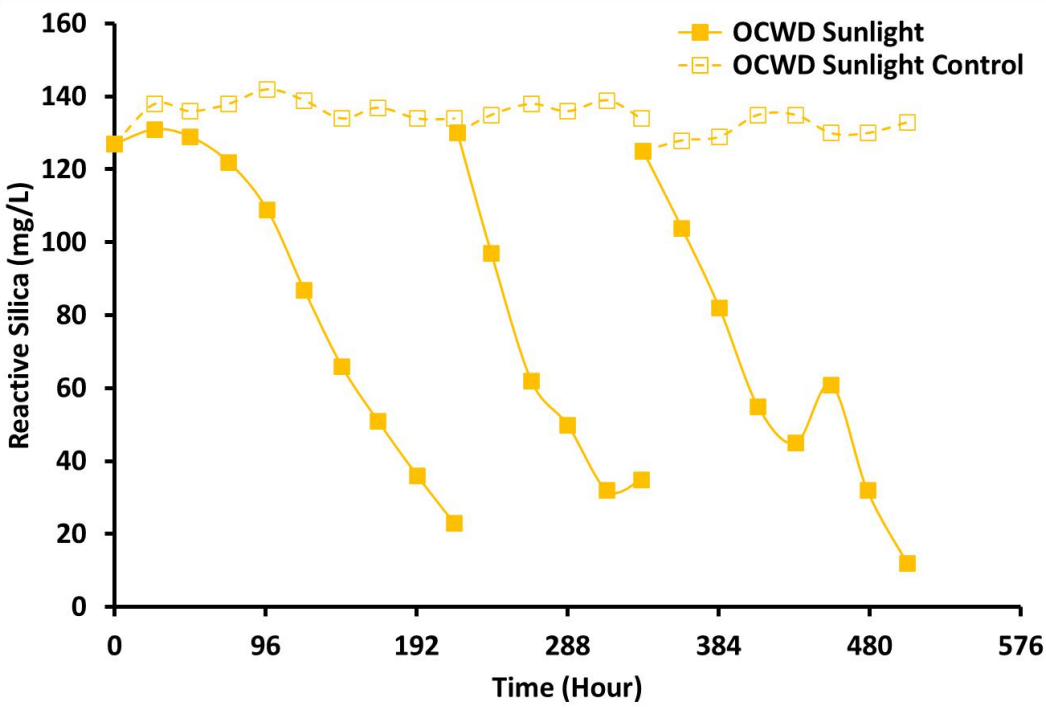


Figure 4-54. Silica uptake for sunlight outdoor experiment with OCWD GWRS ROC
(Temperature: 21 ± 5 °C, PAR: 13 ~ 606 µmol m^{-2} s^{-1}, Sunlight, initial biomass concentration: 0.210 g/L)

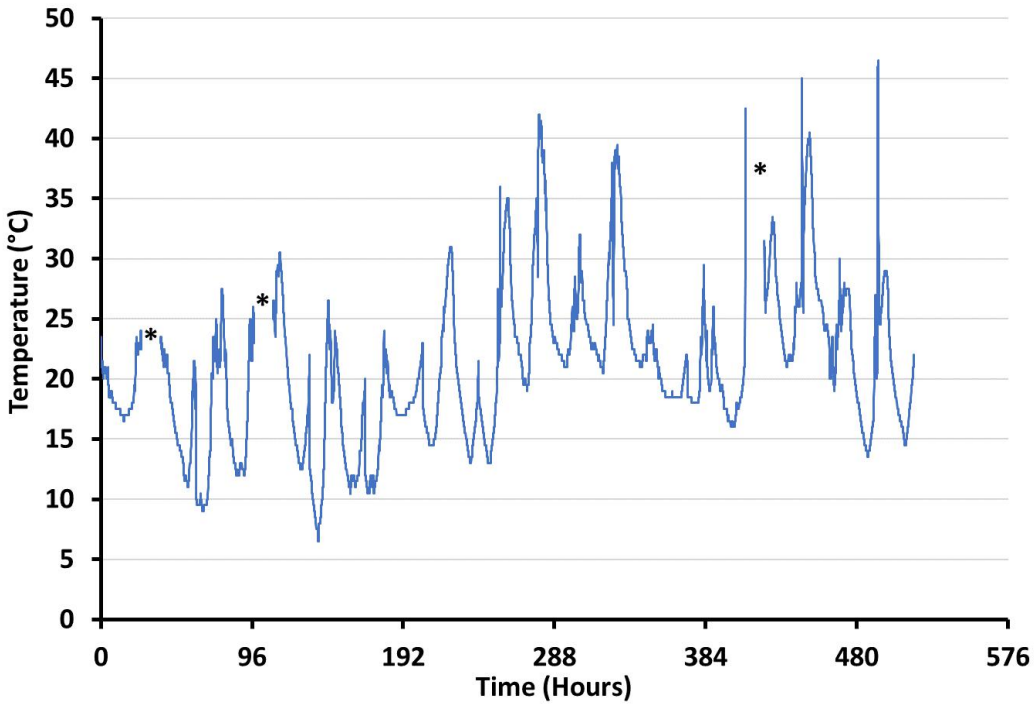


Figure 4-55. Temperature data for outdoor experiment (3rd run) with OCWD GWRS ROC, *: data missing
(See Figure 4-54 for the experimental conditions)

Figure 4-56 below shows the photomicrograph of the third run of outdoor experiment. Unlike the diatoms in the previous two runs which were seriously aggregated and/or bleached, the diatoms looked healthier and greener. Figures 4-57 and 4-58 shows the hourly measurement of PAR and UV on May 14, 2021, which was partially cloudy and sunny. The data without lid were relatively high, especially for UV. With the white lid, the UV drastically decreased to ≤0.2 W m^{-2}. The NDMA and NMOR concentrations shown in Figures 4-59 and 4-60 decreased to <15 ng/L and <43 ng/L, respectively, at the end of each cycle.

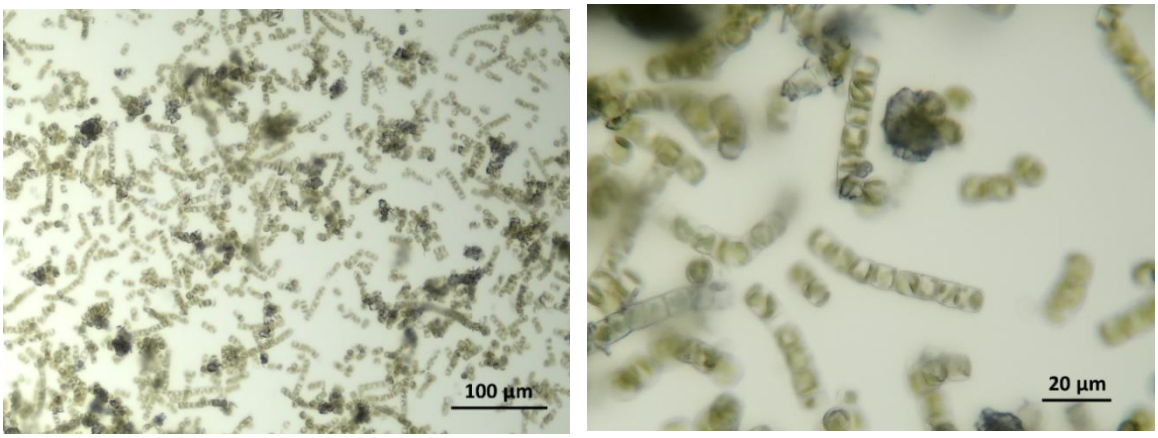


Figure 4-56. Photomicrograph of the 3rd run outdoor experiment

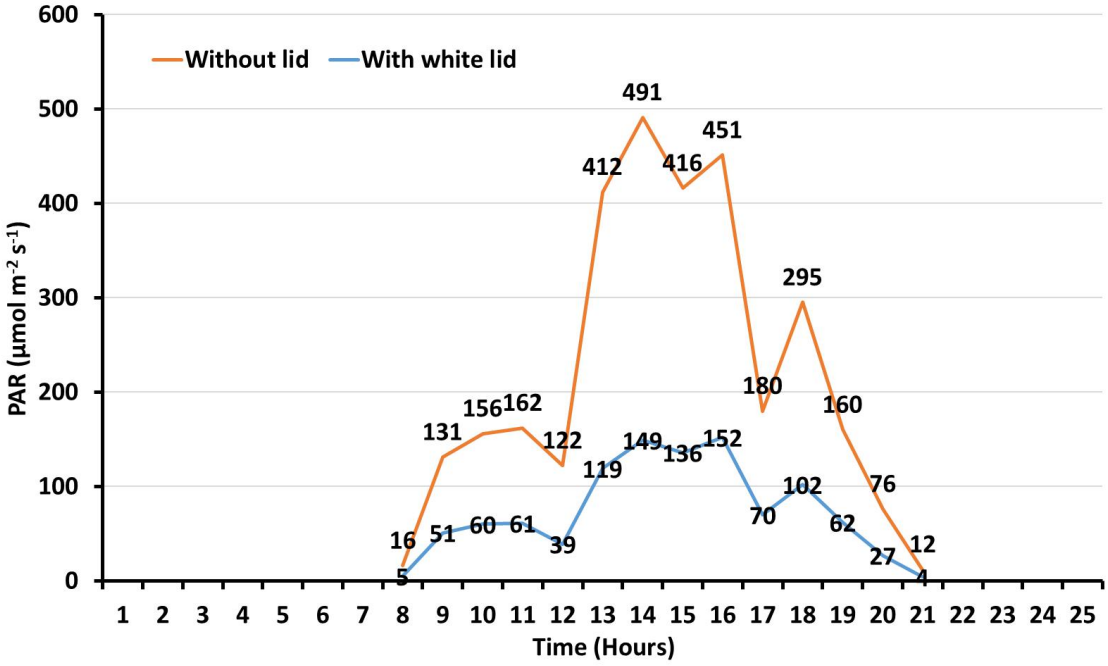


Figure 4-57. Hourly PAR measurement from 7:00 am to 8:00 pm on May 14, 2021

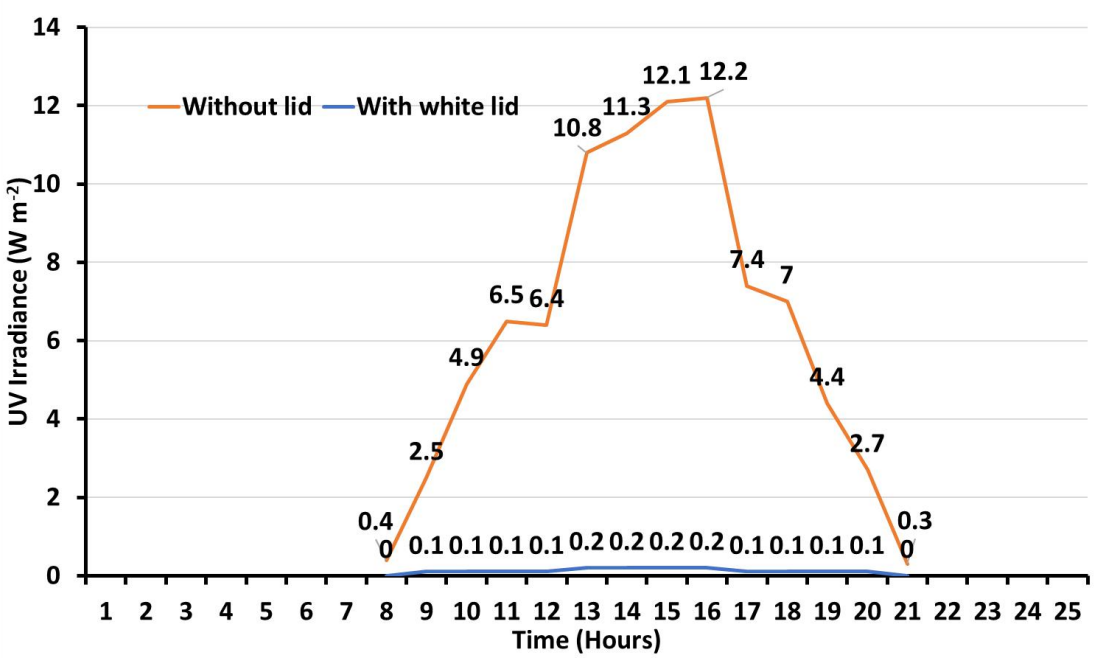


Figure 4-58. Hourly UV measurement from 7:00 am to 8:00 pm on May 14, 2021

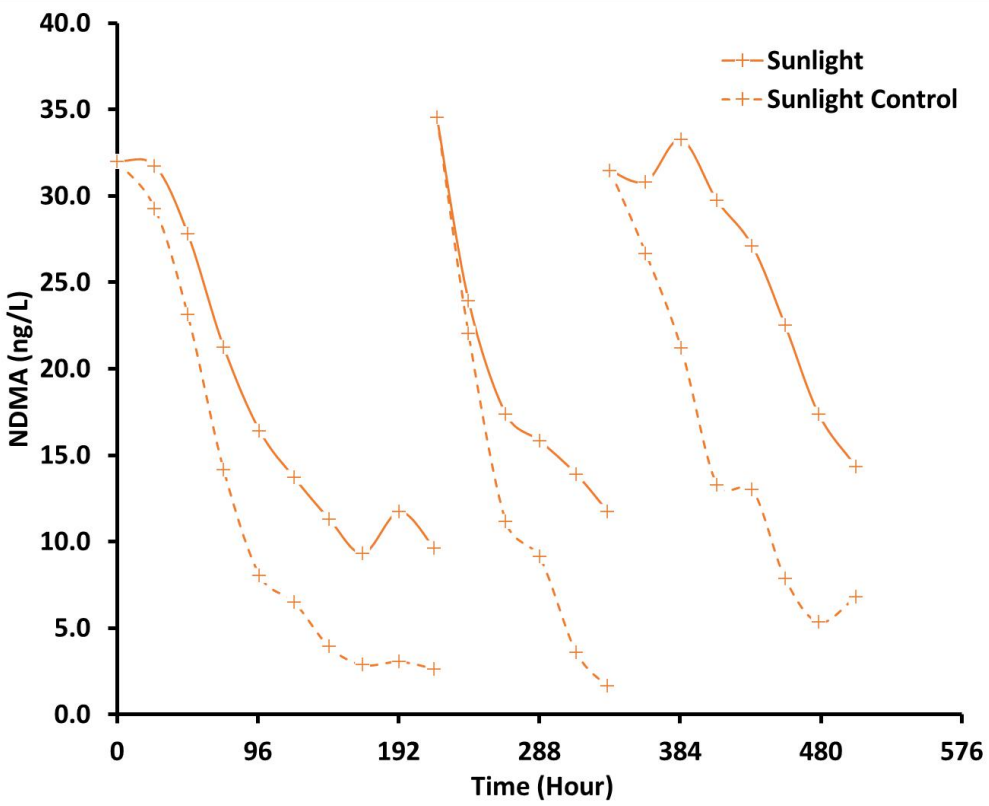


Figure 4-59. NDMA concentration for outdoor experiment (3rd run)
(See Figures 4-53 and 4-54 for the experimental conditions)

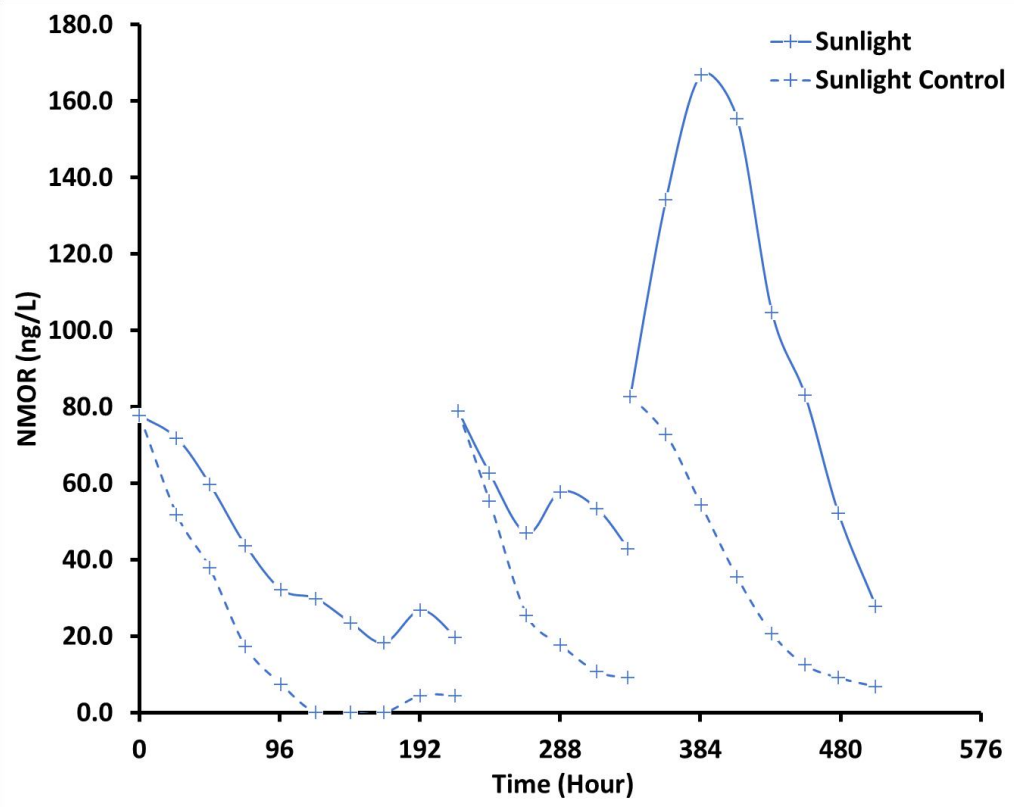


Figure 4-60. NMOR concentration for outdoor experiment (3rd run)
(See Figures 4-53 and 4-54 for the experimental conditions)

V. FULL-SCALE IMPLICATIONS

Table 5-1 below shows the highest values of average silica uptake rates in OCWD GWRS and SAWS H2Oaks ROCs. The highest average silica uptake rate with OCWD GWRS ROC was 62 mg/L/day in the outdoor/*N*-nitrosamines investigation experiment, with 500 mL jar (temperature: 24 ± 0.5 °C, PAR: 200 ± 5 µmol m^{-2} s^{-1}, 10 W LED, 2,700 K). The highest silica uptake rate with SAWS H2Oaks ROC was 44 mg/L/day in light intensities comparison experiment (with PAR = 510 µmol m^{-2} s^{-1}, temperature: 23 ± 1 °C, 10 W LED, 2,700 K). But PAR equal to 200 µmol m^{-2} s^{-1} (43 mg/L/day) was preferred in the subsequent experiments due to less cost.

Table 5-1. Highest average silica uptake rates (mg/L/day) (all cycles) comparison in seven experiments

Experiment	OCWD GWRS ROC	SAWS H2Oak ROC
Treatability study	31 ± 9	19 ± 4
Light temperatures comparison	41 ± 1 (5,000 K)	37 ± 3 (5,000 K)
Light colors comparison	29 ± 1 (Blue Light)	27 ± 4 (White Light)
Light intensities comparison	49 ± 3 (510 µmol m^{-2} s^{-1})	44 ± 4 (510 µmol m^{-2} s^{-1})
Intermittent & Continuous light comparison	41 ± 3 (Continuous Light)	40 ± 3 (Continuous Light)
Incubation temperatures comparison	39 ± 1 (23 °C)	39 ± 2 (30 °C)
Outdoor/*N*-nitrosamines investigation experiment (LED)	62 ± 8	Not tested
Outdoor/*N*-nitrosamines investigation experiment (Sunlight)	17 ± 2	Not tested

OCWD GWRS produces 17.6MGD (million gallons per day) of RO concentrate daily. Assuming >50% silica removal to achieve 50% fresh water recovery in the

secondary RO. According to the equations mentioned in the objective section, which is also shown below.

$$t_0 = (C_0 - C_t)/k \quad [1]$$

$$V = Qt_0 \quad [2]$$

With initial silica concentration (C_0) of 130 mg/L and final mass concentration (C_t) of 60 mg/L. The time (t_0) (in days) needed to reach desirable silica uptake should be:

$$t_0 = \frac{\left(130\frac{mg}{L} - 60\frac{mg}{L}\right)}{62\ mg/L/day} = 1.13 \text{ days}$$

With treatment time of around 1.13 days and volumetric flow rate of 17.6 MGD. The volume of the photobioreactor should be:

$$V = 17.6\ MGD * 1.13\ days = 19.88 \text{ million gallons}$$

If the depth of the photobioreactor was assumed to be 2 feet (h), then the surface area should be:

$$A = \frac{V}{h} = \frac{19.88\ million\ gallons}{2\ feet} = 1{,}330{,}000 \text{ ft}^2$$

As shown in Figure 5-1 below, the photobioreactor is 2 feet deep, with 1,330 ft of length and 1,000 ft of width, and total volume of 1,330,000 ft^2.

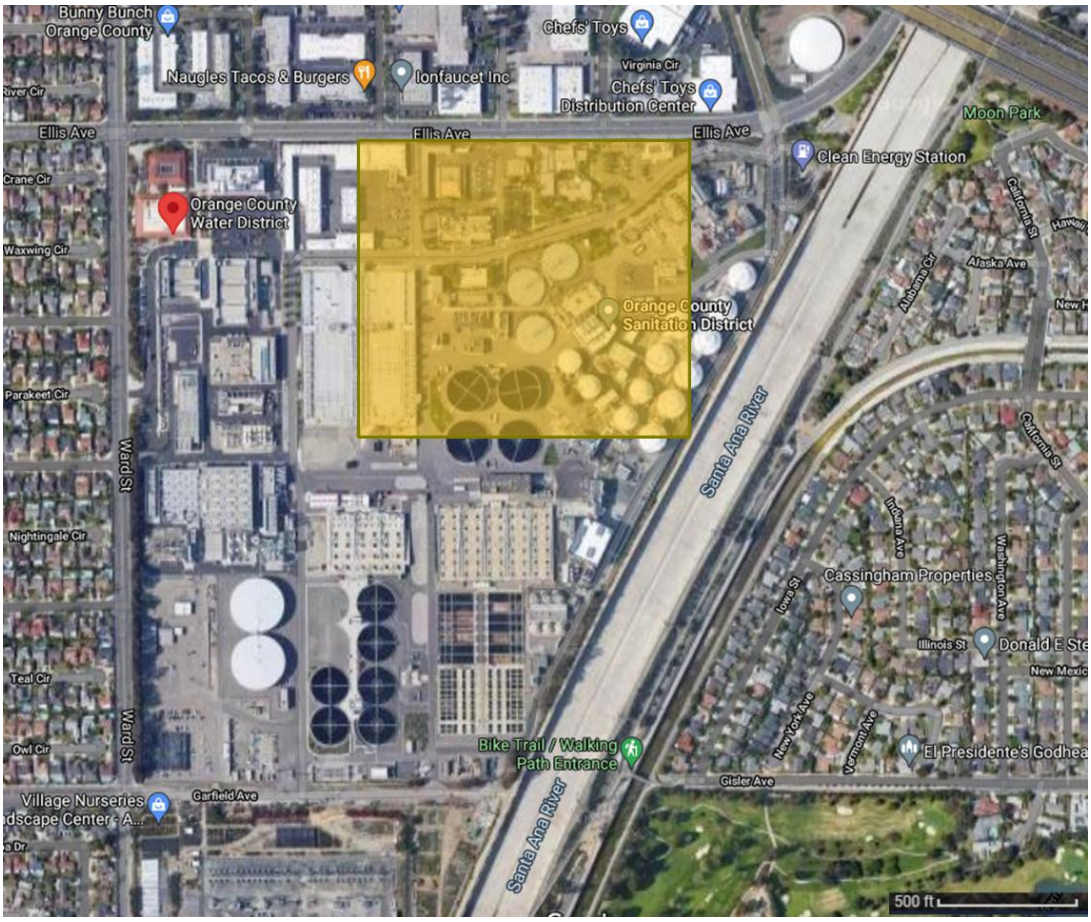


Figure 5-1. Estimated footprint (a blue rectangle: 1,330' × 1,000' × 2') of a full-scale photobioreactor for the OCWD GWRS
(Source: Google Maps)

The same for SAWS H2Oaks ROC. With the same parameter as SAWS H2Oaks, except highest silica uptake rate of 44 mg/L/day and daily ROC production of 1.11 MGD. The estimated photobioreactor should be:

$$t_0 = \frac{\left(130\frac{mg}{L} - 60\frac{mg}{L}\right)}{44\ mg/L/day} = 1.6 \text{ days}$$

$$V = 1.11\ MGD * 1.6\ days = 1.776 \text{ million gallons}$$

$$A = \frac{V}{h} = \frac{1.776\ million\ gallons}{2\ feet} = 120{,}000 \text{ ft}^2$$

As shown in the map of SAWS H2Oaks Center (Figure 5-2), the estimated

footprint of a full-scale photobioreactor will be 600 ft of length and 200 ft of width with 2 feet deep, and total volume of 120,000 ft^2.

Figure 5-2. Estimated footprint (a blue rectangle: 600’ × 200’ × 2’) of a full-scale photobioreactor for the SAWS H2Oaks Center
(Source: Google Maps)

VI. CONCLUSIONS

To increase available freshwater resources and reduce ROC waste volume, a diatom-based photobiological treatment with brackish water diatom *G. flavovirens* was developed. For increasing treatment efficiency and mitigate membrane scaling of combined secondary RO, inorganic scalants such as silica, calcium should be decreased to desired concentrations (>50% or more). The purpose of my research was to optimize and accelerate the silica uptake to reduce the volume of photobioreactor and capital cost. Two ROCs from OCWD GWRS and SAWS H2Oaks center were used as model ROCs from AWPF and BWDF. In the preliminary experiment, light source was confirmed as essential for the photobiological treatment. The SAWS H2Oaks ROC required supplementary of 4 mg/L orthophosphate and 10 mg/L nitrate-N for repeatable semi batch treatment with silica uptake (>85%). In the factors comparison experiments, light temperatures (2,700, 3,000, 4,000 and 5,000 K) and light colors (red, green, yellow, blue, and white) did not impact the silica uptake rates significantly. Light intensity of 200 μmol m^{-2} s^{-1} was found to be sufficient for the photobiological treatment. Intermittent light with 12 hours light and 12 hours dark did not slow down the silica uptake rate. Furthermore, the optimum temperature for the photobiological treatment was found to be 23 to 30 °C. Other four ROCs from different AWPFs and BWDFs were tested and confirmed the treatability with the diatom-based photobiological treatment, excluding the one from West Basin Municipal Water District, which has a high concentration of ammonia (~310 mg/L as N) and known to be toxic for the diatom treatment in previous studies. It was confirmed that sunlight could be used as a light source if the UV irradiation and temperature were carefully controlled. Two *N*-nitrosamines, NDMA and NMOR, in

OCWD GWRS ROC could be degraded simultaneously by the diatom-based photobiological treatment using sunlight as a light source.

Based on the experimental results, the highest silica uptake for OCWD GWRS and SAWS H2Oaks ROCs were 62 and 44 mg/L/day, respectively. If set the desired silica concentration prior to secondary RO to be 60 mg/L, a 1,330' × 1,000' × 2' photobioreactor need to be built on the site of OCWD GWRS to treat 17.6 MGD of ROC, while the size will be 600' × 200' × 2' for SAWS H2Oaks Center to treat 1.11 MGD of ROC. The study showed a great potential that the diatom-based photobiological treatment can be an alternative option for ROC management, especially for inland AWPFs and BWDFs.

There were many unsolved questions and challenges that needed further studies, such as,

- Biomass characterization
- Continuous flow pilot studies
- Secondary RO verification of photobiologically treated ROC
- Contamination control of outdoor experiments
    - Contamination by heterotrophic organisms (such as bacteria and fungi) can be a problem.
- Mineralogical and elemental examination of precipitates. They could be:
    - Calcium carbonate
    - Ammonium magnesium phosphate
    - Hydroxyapatite
    - Calcium phosphate

    - Other contaminating microorganisms (such as fungi)
- Lifecycle cost analysis of the photobiological treatment technology including photobioreactors and secondary RO

APPENDIX SECTION

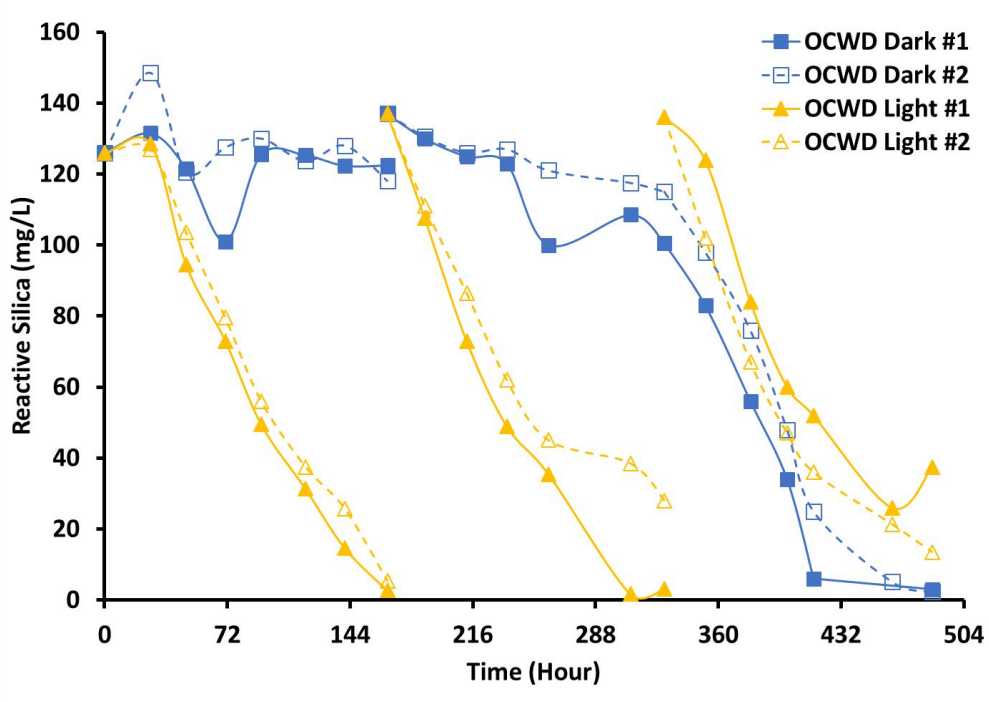
LIGHT & DARK EXPERIMENT

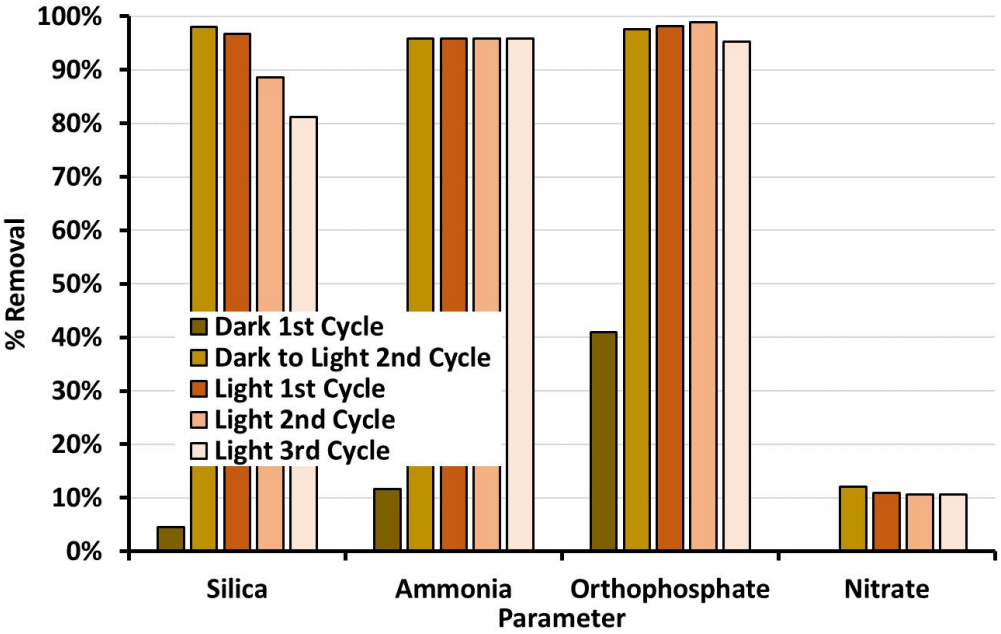
Cycle No.	First Cycle				
Parameter	Initial OCWD	OCWD dark #1	OCWD dark #2	OCWD light #1	OCWD light #2
Silica (mg/L SiO_2)	126	122.5	118.1	2.7	5.4
Nitrate (mg/L as N)	64.7	64.5	64.4	58	57.3
Ammonia (mg/L as N)	9.7	8.55	8.6	< 0.4	< 0.4
Orthophosphate (mg/L as PO_4^{3-})	10.6	6.55	5.95	0.2	0.175
Iron (mg/L)	0.10	0.17	0.07	0.07	0.07
Total chemical oxygen demand (mg/L)	126	140	128	160	148
Biomass (g)	0.0176	\	\	\	\
Color at 455 nm (PtCo unit)	113	150	127	103	137

Cycle No.	Second Cycle				
Parameter	Initial OCWD	OCWD dark #1	OCWD dark #2	OCWD light #1	OCWD light #2
Silica (mg/L SiO_2)	137	3	2.3	3.2	28
Nitrate (mg/L as N)	63.7	55	57	55.9	57.9
Ammonia (mg/L as N)	9.7	< 0.4	< 0.4	< 0.4	< 0.4
Orthophosphate (mg/L as PO_4^{3-})	11.08	0.3	0.23	0.13	0.1
Iron (mg/L)	0.27	0.00	0.03	0.03	0.03
Total chemical oxygen demand (mg/L)	122	150	164	134	146
Biomass (g)	\	0.059	0.0548	\	\
Color at 455 nm (PtCo unit)	133	125	152	80	120

Cycle No.	Third Cycle		
Parameter	Initial OCWD	OCWD light #1	OCWD light #2
Silica (mg/L SiO_2)	136	37.5	13.5
Nitrate (mg/L as N)	64.1	57.5	57
Ammonia (mg/L as N)	9.8	< 0.4	< 0.4

Orthophosphate (mg/L as PO_4^{3-})	11.55	0.18	0.9
Iron (mg/L)	0.27	0.03	0.00
Total chemical oxygen demand (mg/L)	124	140	132
Biomass (g)	\	0.1668	0.1591
Color at 455 nm (PtCo unit)	120	135	160





OCWD GWRS AND SAWS H2OAKS ROCS COMPARISON EXPERIMENT

Cycle No.	First Cycle		
Parameter	Initial OCWD	OCWD #1	OCWD #2
Silica (mg/L SiO_2)	133.5	2.3	6.7
Nitrate (mg/L as N)	62.2	54.9	56
Ammonia (mg/L as N)	9.3	0	0
Orthophosphate(mg/L as PO_4^{3-})	10.9	0.16	0.24
Iron (mg/L)	0.47	0	0
Manganese (mg/L)	0.384	0.106	0.08
Total chemical oxygen demand (mg/L)	115	148	130
pH	7.9	10.5	10.2
Total hardness (mg/L as $CaCO_3$)	1830	990	970
Alkalinity (mg/L as $CaCO_3$)	880	50	50
Biomass (g)	0.0187	\	\
Color at 455 nm (PtCo unit)	133	130	128
Dissolved chemical oxygen demand (mg/L)	134	150	136
Calcium hardness (mg/L as $CaCO_3$)	1705	560	420
Conductivity (mS/cm)	7.68	4.58	6.45
TDS (mg/L)	5146	3069	4322

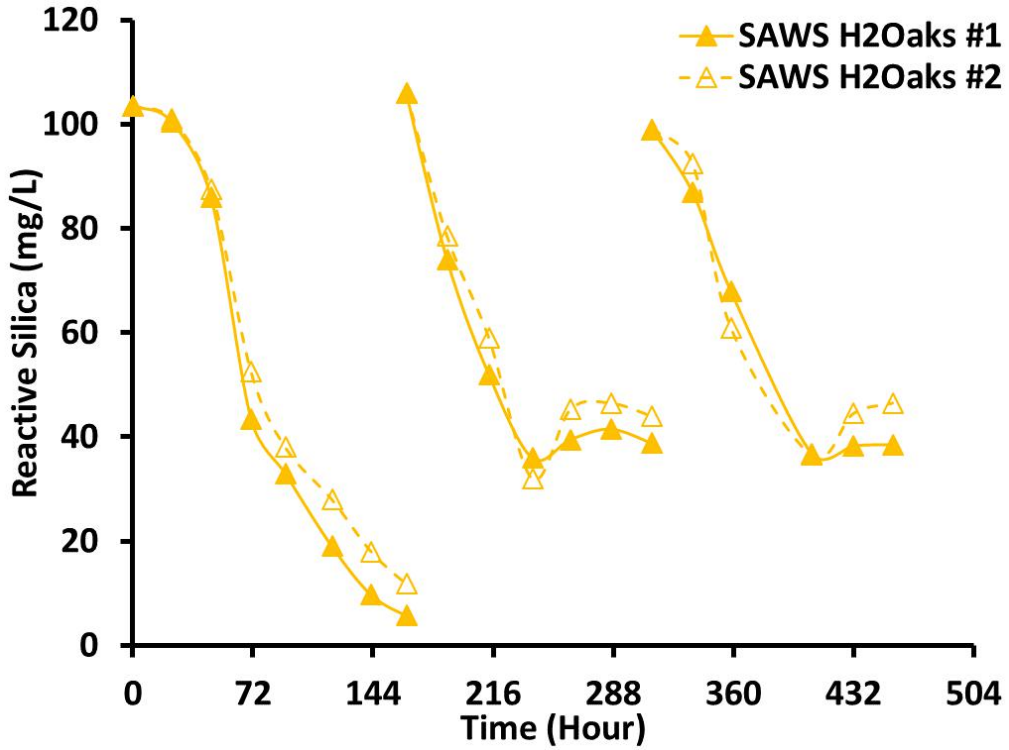
Cycle No.	Second Cycle		
Parameter	Initial OCWD	OCWD #1	OCWD #2
Silica (mg/L SiO_2)	139	3.3	5.5
Nitrate (mg/L as N)	61.9	54.5	53.5
Ammonia (mg/L as N)	10	0.15	0.1
Orthophosphate(mg/L as PO_4^{3-})	10.1	0.2	0.26
Iron (mg/L)	0.42	0.06	0.08
Manganese (mg/L)	0.388	0.082	0.084
Total chemical oxygen demand (mg/L)	128	141	144
pH	8.2	10.3	9.1
Total hardness (mg/L as $CaCO_3$)	1790	970	950
Alkalinity (mg/L as $CaCO_3$)	850	60	60
Biomass (g)	\	\	\
Color at 455 nm (PtCo unit)	165	148	137
Dissolved chemical oxygen demand (mg/L)	\	\	\
Calcium hardness (mg/L as $CaCO_3$)	1745	390	380
Conductivity (mS/cm)	7.66	6.29	6.33
TDS (mg/L)	5132	4214	4241

Cycle No.	Third Cycle		
Parameter	Initial OCWD	OCWD #1	OCWD #2
Silica (mg/L SiO_2)	138	12.8	17.5
Nitrate (mg/L as N)	62	58.4	58.9
Ammonia (mg/L as N)	9.9	0.1	0.1
Orthophosphate(mg/L as PO_4^{3-})	12.2	0.36	0.32
Iron (mg/L)	0.45	0	0.04
Manganese (mg/L)	0.426	0.092	0.12
Total chemical oxygen demand (mg/L)	128	144	144
pH	7.9	8.8	7.4
Total hardness (mg/L as $CaCO_3$)	1820	1040	1080
Alkalinity (mg/L as $CaCO_3$)	840	110	120
Biomass (g)	\	0.341	0.2959
Color at 455 nm (PtCo unit)	160	148	132
Dissolved chemical oxygen demand (mg/L)	\	\	\
Calcium hardness (mg/L as $CaCO_3$)	1675	290	420
Conductivity (mS/cm)	7.5	6.63	6.84
TDS (mg/L)	5025	4442	4583

Cycle No.	First Cycle		
Parameter	Initial SAWS	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	105	5.7	11.8
Nitrate (mg/L as N)	0	0	0
Ammonia (mg/L as N)	8.2	< 0.4	< 0.4
Orthophosphate(mg/L as PO_4^{3-})	1.5	0.24	0.26
Iron (mg/L)	0.17	0	0
Manganese (mg/L)	0.41	0.03	0.028
Total chemical oxygen demand (mg/L)	38	76	66
pH	8	11.1	10.3
Total hardness (mg/L as $CaCO_3$)	930	460	410
Alkalinity (mg/L as $CaCO_3$)	1360	810	740
Biomass (g)	0.0213	\	\
Color at 455 nm (PtCo unit)	5	63	65
Dissolved chemical oxygen demand (mg/L)	56	80	78
Calcium hardness (mg/L as $CaCO_3$)	805	90	70
Conductivity (mS/cm)	15.11	14.44	14.44
TDS (mg/L)	10124	9675	9675

Cycle No.	Second Cycle		
Parameter	Initial SAWS	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	106	38.8	44
Nitrate (mg/L as N)	0	0	0
Ammonia (mg/L as N)	8.8	< 0.4	< 0.4
Orthophosphate(mg/L as PO_4^{3-})	1.79	0.08	0.08
Iron (mg/L)	0.11	0.16	0.12
Manganese (mg/L)	0.424	0.04	0.026
Total chemical oxygen demand (mg/L)	68	64	64
pH	8.4	9.3	8.3
Total hardness (mg/L as $CaCO_3$)	940	510	520
Alkalinity (mg/L as $CaCO_3$)	1370	850	860
Biomass (g)	\	\	\
Color at 455 nm (PtCo unit)	5	36	24
Dissolved chemical oxygen demand (mg/L)	\	\	\
Calcium hardness (mg/L as $CaCO_3$)	705	90	160
Conductivity (mS/cm)	14.98	14.16	12.12
TDS (mg/L)	10037	9487	8120

Cycle No.	Third Cycle		
Parameter	Initial SAWS	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	99	32.9	40
Nitrate (mg/L as N)	0.23	<0.23	<0.23
Ammonia (mg/L as N)	8.9	<0.4	<0.4
Orthophosphate(mg/L as PO_4^{3-})	1.78	0.1	0.06
Iron (mg/L)	0.26	0.04	0.08
Manganese (mg/L)	0.418	0.07	0.058
Total chemical oxygen demand (mg/L)	50	56	48
pH	8.1	8.2	8.1
Total hardness (mg/L as $CaCO_3$)	940	520	500
Alkalinity (mg/L as $CaCO_3$)	1410	880	920
Biomass (g)	\	0.1574	0.1588
Color at 455 nm (PtCo unit)	6	94	74
Dissolved chemical oxygen demand (mg/L)	\	\	\
Calcium hardness (mg/L as $CaCO_3$)	770	110	40
Conductivity (mS/cm)	15.03	14.56	14.64
TDS (mg/L)	10070	9755	9810


SAWS H2Oaks #1
SAWS H2Oaks #2
Reactive Silica (mg/L)
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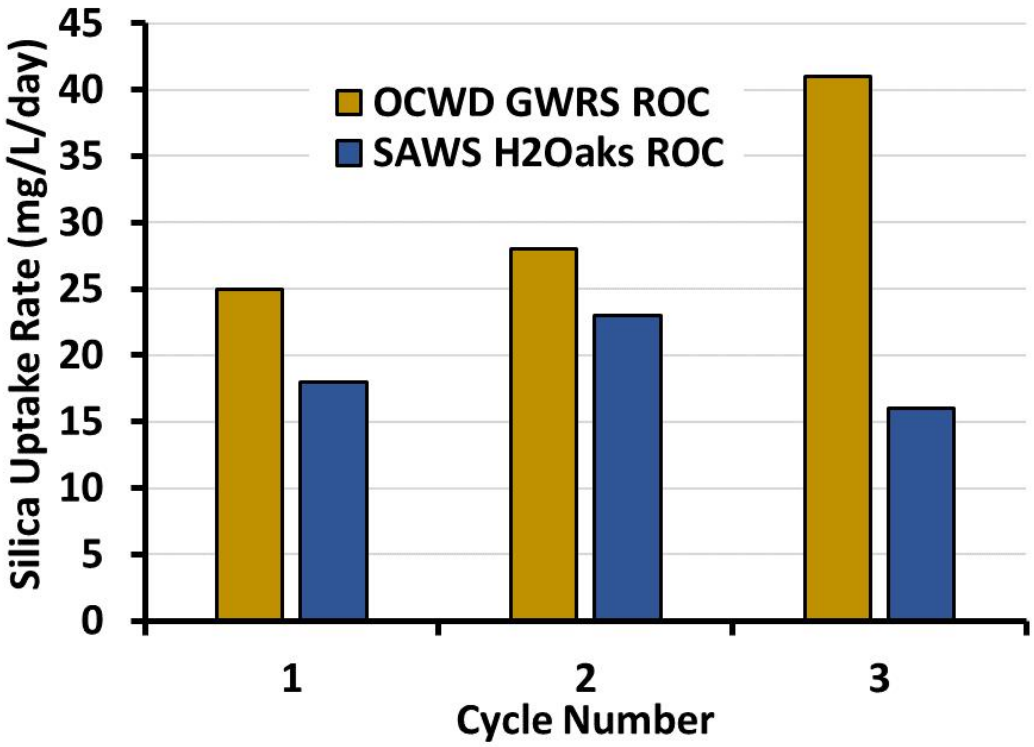
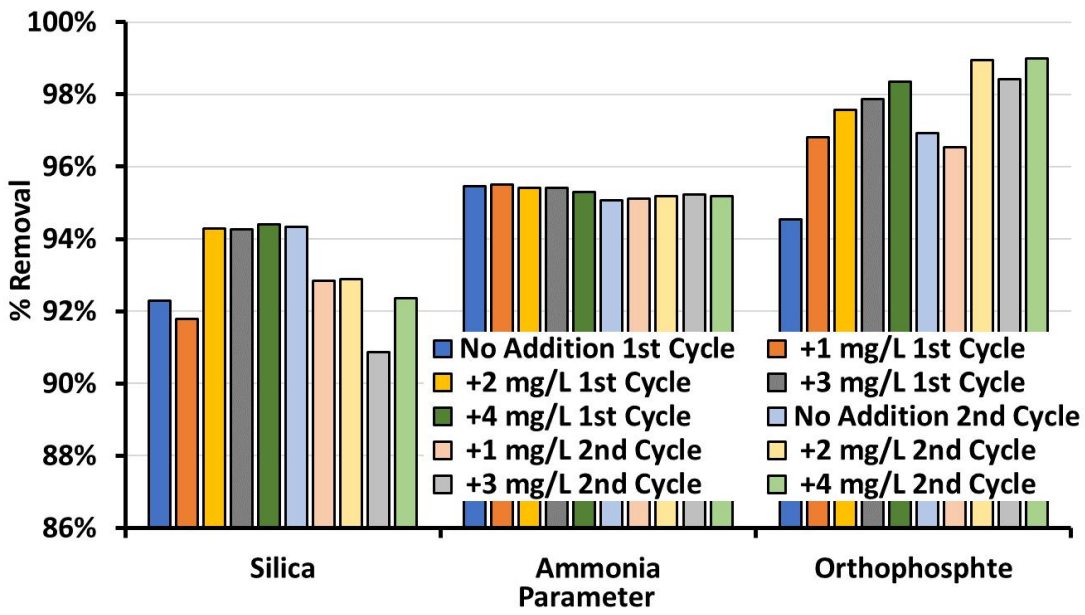
100
80
60
40
20
0
0
72
144
216
288
360
432
504
Time (Hour)


OCWD GWRS ROC
SAWS H2Oaks ROC
Silica Uptake Rate (mg/L/day)
45
40
35
30
25
20
15
10
5
0
1
2
3
Cycle Number

NUTRIENTS OPTIMIZATION EXPERIMENT



Initial data of 1st cycle	No addition	Add 1 mg/L OP	Add 2 mg/L OP	Add 3 mg/L OP	Add 4 mg/L OP
Silica Conc.(mg/L SiO_2)	120.5	134	133	134.5	137.5
Color at 455 nm (PtCo unit)	13.3	3.3	10	6.7	6.7
Orthophosphate(mg/L as PO_4^{3-})	1.83	2.83	3.7	4.23	6.63
Ammonia (mg/L as N)	8.8	8.9	8.7	8.7	8.5

Initial data of 2nd cycle	No addition	Add 1 mg/L OP	Add 2 mg/L OP	Add 3 mg/L OP	Add 4 mg/L OP
Silica Conc.(mg/L SiO_2)	132.5	135.5	140.5	139	127
Color at 455 nm (PtCo unit)	26.7	20	13.3	13.3	20
Orthophosphate(mg/L as PO_4^{3-})	1.3	2.6	4.8	5.7	6.9
Ammonia (mg/L as N)	8.1	8.2	8.3	8.4	8.3

Cycle No.	First Cycle				
Parameter	No	Add 1	Add 2	Add 3	Add 4

	addition	mg/L OP	mg/L OP	mg/L OP	mg/L OP
Silica (mg/L SiO_2)	9.3	11	7.6	7.7	7.7
Color at 455 nm (PtCo unit)	70.5	65	58	77	76
Orthophosphate(mg/L as PO_4^{3-})	0.1	0.09	0.09	0.09	0.11
Ammonia (mg/L as N)	<0.4	<0.4	<0.4	<0.4	<0.4

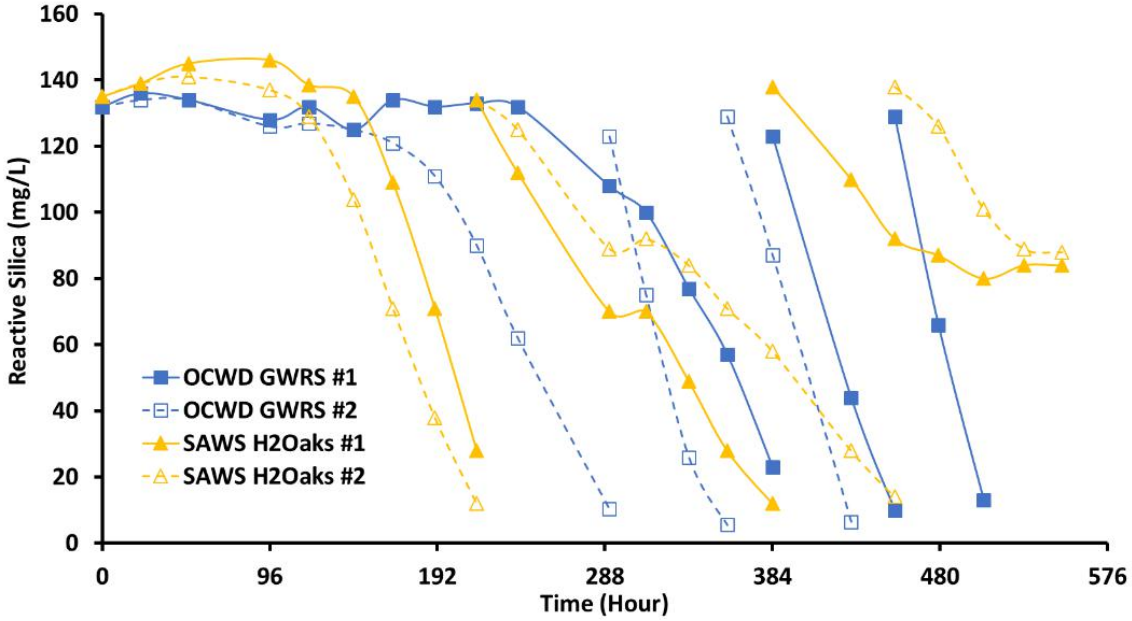
Cycle No.	Second Cycle				
Parameter	No addition	Add 1 mg/L OP	Add 2 mg/L OP	Add 3 mg/L OP	Add 4 mg/L OP
Silica (mg/L SiO_2)	7.5	9.7	10	12.7	9.7
Color at 455 nm (PtCo unit)	47	54	50	50	53
Orthophosphate(mg/L as PO_4^{3-})	0.04	0.09	0.05	0.09	0.07
Ammonia (mg/L as N)	<0.4	<0.4	<0.4	<0.4	<0.4

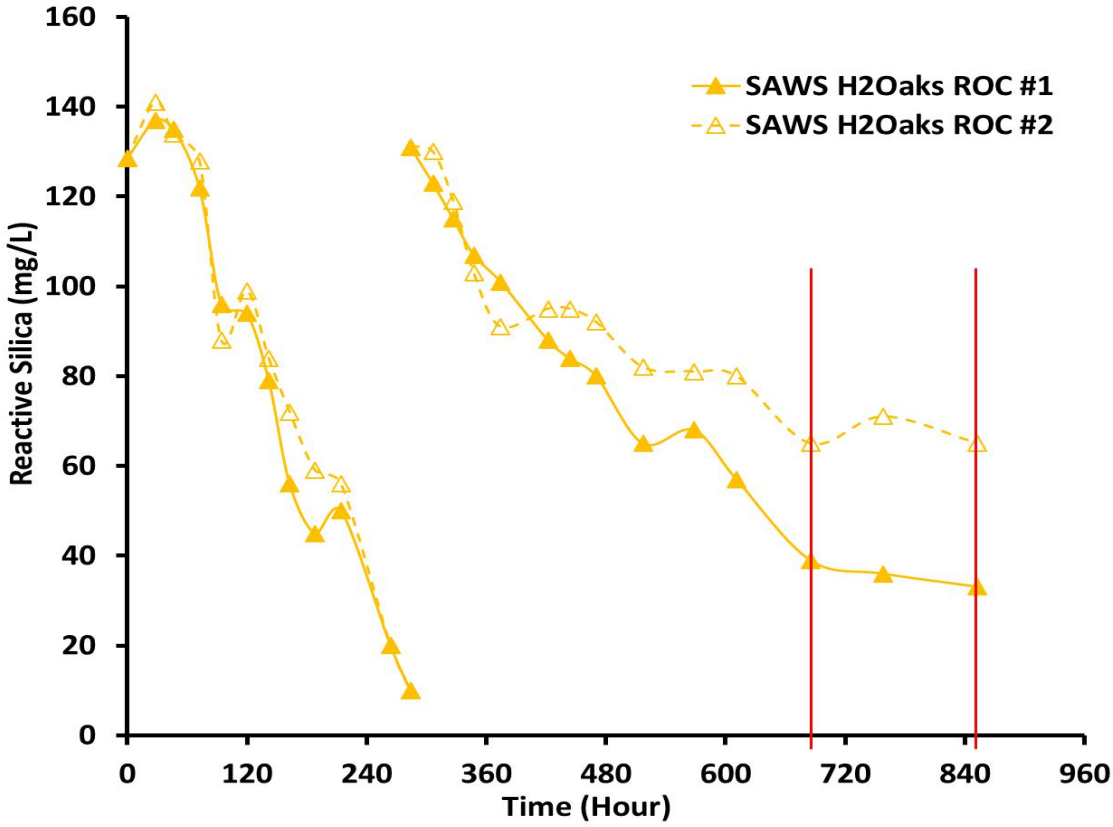
Cycle No.	First Cycle					
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	132	140	23	10.3	28	12
Nitrate (mg/L as N)	64.6	\	61.5	41	\	\
Ammonia (mg/L as N)	11	5.2	0.4	<0.4	<0.4	<0.4
Orthophosphate(mg/L as PO_4^{3-})	11.2	1.68	0.1	0.11	0.14	0.16
Color at 455 nm (PtCo unit)	140	23	136	168	105	106
Filtered UV_{254}	0.765	0.115	0.746	0.789	0.157	0.182
Chlorophyll (ug/L)	45.68	1.987	18.26	25.38	7.042	6.642
phycocyanin (ppb)	18.56	0	3.397	18.95	0	0
Dissolved chemical oxygen demand (mg/L)	118	40	116	138	60	74
Total chemical oxygen demand (mg/L)	130	56	120	132	70	70
Biomass (g)	0.0271	0.0271	\	\	\	\

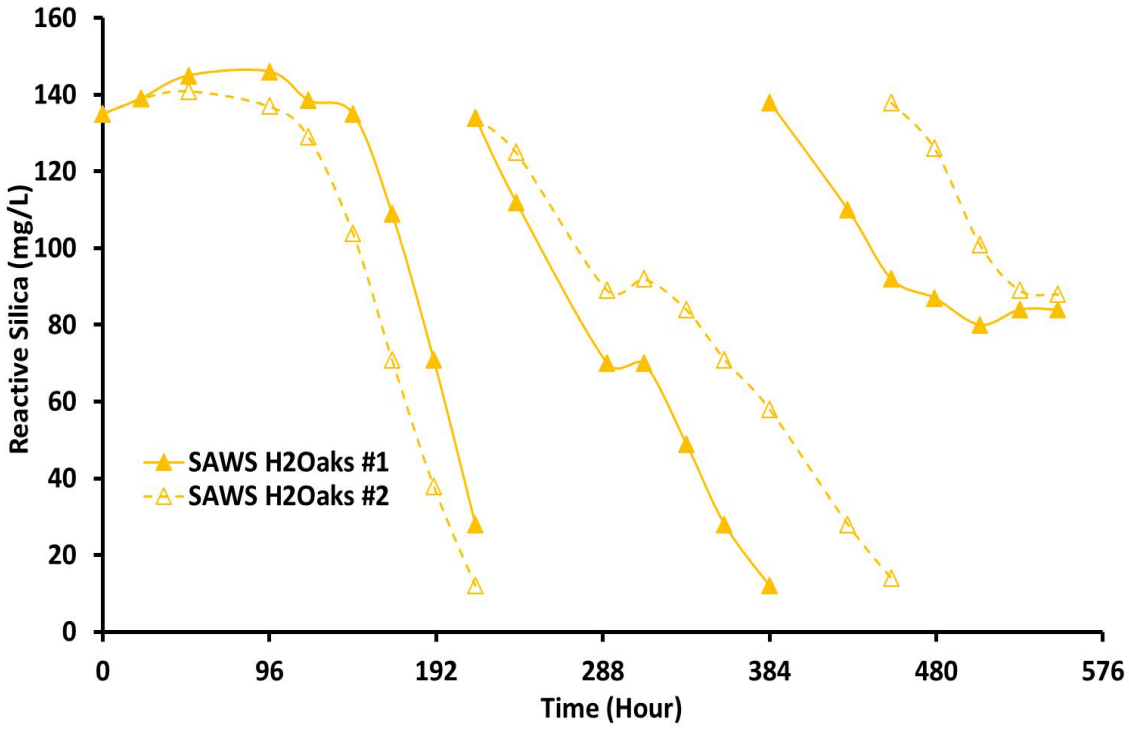
Cycle No.	Second Cycle

Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	123	134	10	5.5	12	14
Nitrate (mg/L as N)	61.5	\	55.7	45.3	\	\
Ammonia (mg/L as N)	11.1	4.36	0.6	<0.4	<0.4	<0.4
Orthophosphate(mg/L as PO_4^{3-})	11.4	1.65	0.12	0.09	0.21	0.14
Color at 455 nm (PtCo unit)	155	12	137	153	73	94
Filtered UV_{254}	\	\	\	\	\	\
Chlorophyll (ug/L)	47.1	2.493	27.63	26.66	6.242	7.439
phycocyanin (ppb)	8.62	0.403	0	2.343	0	1.078
Dissolved chemical oxygen demand (mg/L)	122	50	\	\	\	\
Total chemical oxygen demand (mg/L)	132	44	\	\	\	\
Biomass (g)	\	\	\	\	\	\

Cycle No.	Third Cycle					
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	129	138	13	6.5	84	88
Nitrate (mg/L as N)	63.3	\	56.9	54.4	\	\
Ammonia (mg/L as N)	10.4	3.6	<0.4	0.4	<0.4	<0.4
Orthophosphate(mg/L as PO_4^{3-})	11.9	1.8	0.14	0.11	0.28	0.37
Color at 455 nm (PtCo unit)	125	12	167	201	69	64
Filtered UV_{254}	\	\	\	\	\	\
Chlorophyll (ug/L)	46.84	2.128	29.68	27.88	6.312	4.172
phycocyanin (ppb)	8.028	0	0.9	15.38	0	0
Dissolved chemical oxygen demand (mg/L)	\	\	\	\	\	\
Total chemical oxygen demand (mg/L)	\	\	\	\	\	\
Biomass (g)	\	\	0.2653	0.2509	0.0931	0.0917


Reactive Silica (mg/L)
Time (Hour)
OCWD GWRS #1
OCWD GWRS #2
SAWS H2Oaks #1
SAWS H2Oaks #2
0
20
40
60
80
100
120
140
160
0
96
192
288
384
480
576


Reactive Silica (mg/L)
Time (Hour)
SAWS H2Oaks ROC #1
SAWS H2Oaks ROC #2
0
20
40
60
80
100
120
140
160
0
120
240
360
480
600
720
840
960


160
140
120
100
80
60
40
20
0
Reactive Silica (mg/L)
SAWS H2Oaks #1
SAWS H2Oaks #2
0
96
192
288
384
480
576
Time (Hour)

LIGHT TEMPERATURES EXPERIMENT

First Cycle	Initial Bottles		2700 K			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	125	118	14	16	4	6
Nitrate (mg/L as N)	64	10	59.2	60.1	2.82	2.57
Ammonia (mg/L as N)	10.2	9.2	0.4	0.3	0.5	0.2
Orthophosphate (mg/L as PO_4^{3-})	11.3	4.9	0.12	0.18	0.1	0.14
Total chemical oxygen demand (mg/L)	124	40	124	140	80	76
Total hardness (mg/L as $CaCO_3$)	1860	1070	1050	1100	510	510
Calcium hardness (mg/L as $CaCO_3$)	1590	800	450	460	120	120
Color at 455 nm (PtCo unit)	131	4	117	121	52	54
pH	8.6	8.6	9.8	9.5	10.6	10.7
Alkalinity (mg/L as $CaCO_3$)	960	980	120	200	410	340
Filtered UV_{254}	0.8	0.153	0.823	0.796	0.158	0.162
Chlorophyll (ug/L)	2.12	0.064	0.82	0.38	0.449	5.35
Unfiltered Phycocyanin (ppb)	2.819	3.528	14.08	0	7.379	0
Filtered Phycocyanin (ppb)	17.74	0	22.56	4.955	22.55	0
Biomass (g)	0.0127	0.0106	\	\	\	\
Turbidity (NTU)	0.21	0.07	0.35	0.37	1.63	0.99

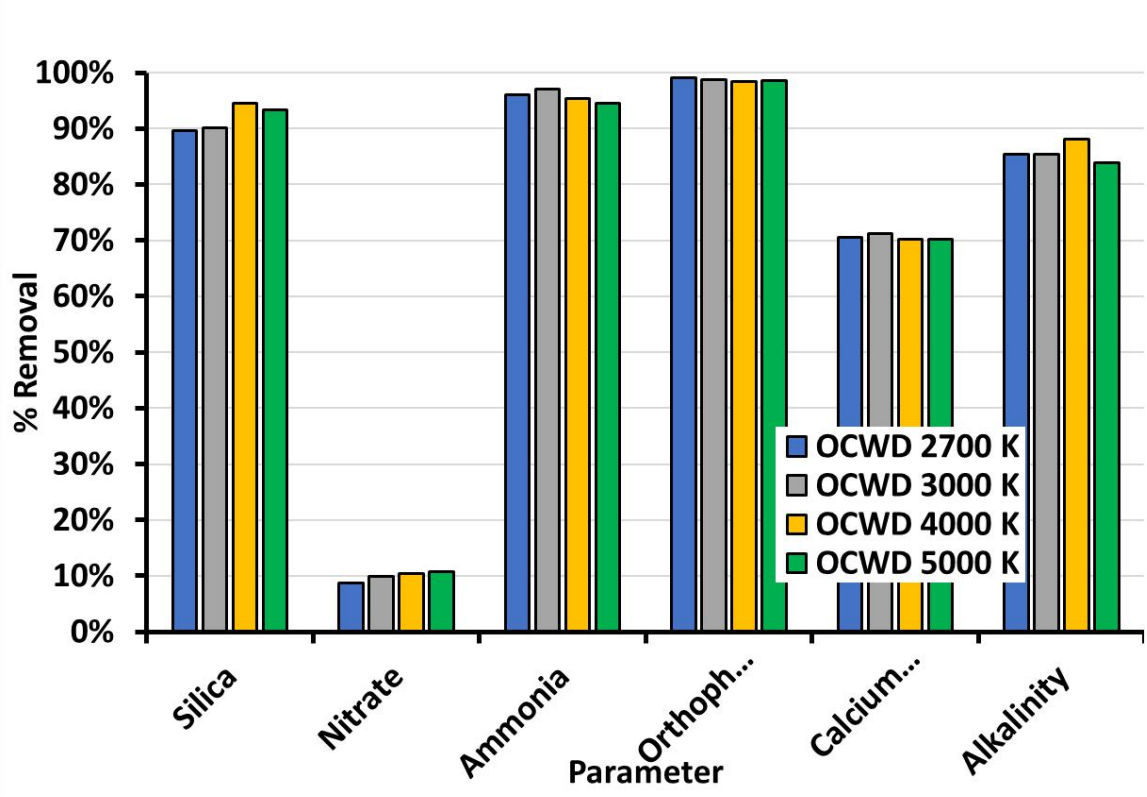
First Cycle	Initial Bottles		3000 K			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	125	118	12	15	13	20
Nitrate (mg/L as N)	64	10	57.7	57.9	2.76	2.41
Ammonia (mg/L as N)	10.2	9.2	0	0.3	0.3	0.4
Orthophosphate (mg/L as PO_4^{3-})	11.3	4.9	0.18	0.22	0.06	0.1
Total chemical oxygen demand (mg/L)	124	40	136	128	64	72
Total hardness (mg/L as	1860	1070	1020	1030	520	520

$CaCO_3$)						
Calcium hardness (mg/L as $CaCO_3$)	1590	800	430	470	130	130
Color at 455 nm (PtCo unit)	131	4	116	125	39	55
pH	8.6	8.6	11	10.8	10.5	10.6
Alkalinity (mg/L as $CaCO_3$)	960	980	130	160	370	390
Filtered UV_{254}	0.8	0.153	0.738	0.805	0.121	0.138
Chlorophyll (ug/L)	2.12	0.064	1.02	0.71	6.093	4.787
Unfiltered Phycocyanin (ppb)	2.819	3.528	6.829	2.191	5.926	13.18
Filtered Phycocyanin (ppb)	17.74	0	11.83	0	7.705	36.57
Biomass (g)	0.0127	0.0106	\	\	\	\
Turbidity (NTU)	0.21	0.07	1.13	1.16	0.22	1.38

First Cycle	Initial Bottles		4000 K			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	125	118	6	12	2	9
Nitrate (mg/L as N)	64	10	57.6	58.8	2.56	2.74
Ammonia (mg/L as N)	10.2	9.2	0.4	0.5	0	0.2
Orthophosphate (mg/L as PO_4^{3-})	11.3	4.9	0.14	0.24	0.1	0.08
Total chemical oxygen demand (mg/L)	124	40	140	136	72	52
Total hardness (mg/L as $CaCO_3$)	1860	1070	970	1040	480	530
Calcium hardness (mg/L as $CaCO_3$)	1590	800	480	520	140	150
Color at 455 nm (PtCo unit)	131	4	100	122	46	52
pH	8.6	8.6	10	9.7	10.7	10.6
Alkalinity (mg/L as $CaCO_3$)	960	980	100	140	400	380
Filtered UV_{254}	0.8	0.153	0.768	0.813	0.183	0.145
Chlorophyll (ug/L)	2.12	0.064	0.36	1.55	1.085	7.871
Unfiltered Phycocyanin (ppb)	2.819	3.528	0	23.88	12.15	0
Filtered Phycocyanin (ppb)	17.74	0	10.44	29.94	5.191	0

Biomass (g)	0.0127	0.0106	\	\	\	\
Turbidity (NTU)	0.21	0.07	2.32	0.66	1.01	1.77

First Cycle	Initial Bottles		5000 K			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	125	118	8	10	6	8
Nitrate (mg/L as N)	64	10	57.9	57.9	2.1	2.27
Ammonia (mg/L as N)	10.2	9.2	0.2	0.4	0.5	0.5
Orthophosphate (mg/L as PO_4^{3-})	11.3	4.9	0.28	0.14	0.08	0.1
Total chemical oxygen demand (mg/L)	124	40	132	124	64	72
Total hardness (mg/L as $CaCO_3$)	1860	1070	1020	1000	480	520
Calcium hardness (mg/L as $CaCO_3$)	1590	800	490	440	150	160
Color at 455 nm (PtCo unit)	131	4	118	120	48	49
pH	8.6	8.6	10.8	10.5	10.6	10.7
Alkalinity (mg/L as $CaCO_3$)	960	980	170	130	350	400
Filtered UV_{254}	0.8	0.153	0.795	0.784	0.183	0.149
Chlorophyll (ug/L)	2.12	0.064	0.14	0.92	5.434	13.158
Unfiltered Phycocyanin (ppb)	2.819	3.528	5.616	0	20.17	21.81
Filtered Phycocyanin (ppb)	17.74	0	26.32	0	0	12.34
Biomass (g)	0.0127	0.0106	\	\	\	\
Turbidity (NTU)	0.21	0.07	1.07	0.79	1.5	1.58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Silica
Nitrate
Ammonia
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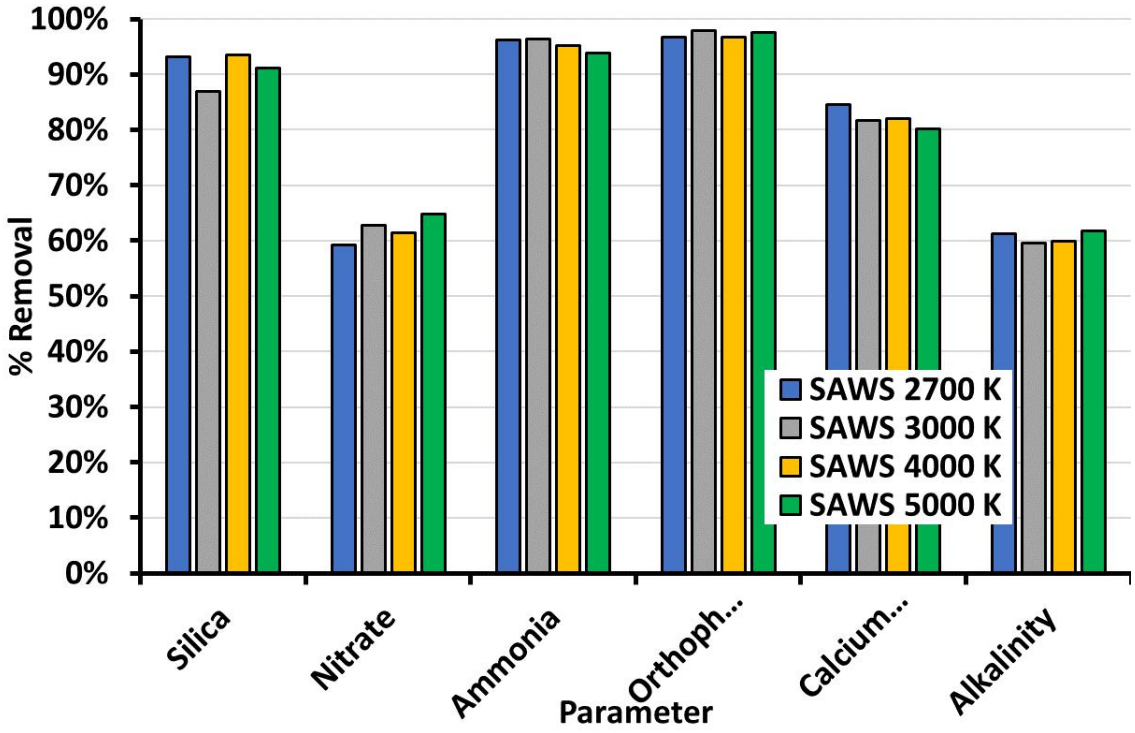
Calcium...
Alkalinity
Parameter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SAWS 5000 K
Silica
Nitrate
Ammonia
Orthoph...
Calcium...
Alkalinity
Parameter

LIGHT COLORS EXPERIMENT

First Cycle	Initial	Red		Green		Yellow	
Parameter	Initial OCWD	O1	O2	O1	O2	O1	O2
Silica (mg/L SiO_2)	129	13	13	19	22	20	17
Nitrate (mg/L as N)	62.3	55.7	55.7	54.3	54.2	55.3	55.1
Ammonia (mg/L as N)	8.2	1.8	1.1	1.2	1	0.4	0.4
Orthophosphate (mg/L as PO_4^{3-})	8.2	0.16	0.2	0.14	0.12	0.16	0.2
Total chemical oxygen demand (mg/L)	144	136	144	124	140	132	132
Dissolved chemical oxygen demand (mg/L)	120	136	132	124	104	132	132
Calcium hardness (mg/L as $CaCO_3$)	1460	320	320	370	320	330	280
Color at 455 nm (PtCo unit)	202	195	200	186	182	200	200
pH	8.2	9.9	10	9.4	9.2	9.6	9.8
Alkalinity (mg/L as $CaCO_3$)	1222	177	187	202	237	222	162
Filtered UV254	0.84	0.81	0.803	0.797	0.797	0.815	0.812
Chlorophyll (ug/L)	5.17	3.46	3.5	2.04	3.08	3.34	3.07
Unfiltered Phycocyanin (ppb)	9.653	0	0	0	27.21	0	0
Filtered Phycocyanin (ppb)	0	0	0	17.89	1.446	0	0
Biomass (g)	0.0343	\	\	\	\	\	\
Turbidity (NTU)	0.28	0.54	0.97	0.45	0.38	1.08	0.33

First Cycle	Initial	Blue		White	
Parameter	Initial OCWD	O1	O2	O1	O2
Silica (mg/L SiO_2)	129	8	9	7	13
Nitrate (mg/L as N)	62.3	55.3	55.2	52.8	53.4
Ammonia (mg/L as N)	8.2	<0.4	0.4	<0.4	<0.4
Orthophosphate (mg/L as PO_4^{3-})	8.2	0.08	0.08	0.1	0.18
Total chemical oxygen	144	144	140	128	144

demand (mg/L)					
Dissolved chemical oxygen demand (mg/L)	120	138	142	148	128
Calcium hardness (mg/L as $CaCO_3$)	1460	330	330	270	270
Color at 455 nm (PtCo unit)	202	171	150	174	176
pH	8.2	9.9	10.1	10.4	9.9
Alkalinity (mg/L as $CaCO_3$)	1222	207	237	152	182
Filtered UV254	0.84	0.766	0.796	0.788	0.799
Chlorophyll (ug/L)	5.17	3.97	3.09	3.59	2.46
Unfiltered Phycocyanin (ppb)	9.653	0	3.736	6.89	0.993
Filtered Phycocyanin (ppb)	0	0	0	0	0
Biomass (g)	0.0343	\	\	\	\
Turbidity (NTU)	0.28	0.34	0.24	2.07	1.25

Second Cycle	Initial	Red		Green		Yellow	
Parameter	Initial OCWD	O1	O2	O1	O2	O1	O2
Silica (mg/L SiO_2)	123	16	3	19	19.5	17	19
Nitrate (mg/L as N)	62.7	53	52.4	52	51.7	53.5	52.9
Ammonia (mg/L as N)	8.9	0.4	<0.4	<0.4	<0.4	0.4	<0.4
Orthophosphate(mg/L as PO_4^{3-})	8.3	0.14	0.12	0.12	0.08	0.12	0.12
Total chemical oxygen demand (mg/L)	128	132	144	136	132	136	148
Dissolved chemical oxygen demand (mg/L)	124	132	124	124	128	132	128
Calcium hardness (mg/L as $CaCO_3$)	1390	370	360	370	310	300	330
Color at 455 nm (PtCo unit)	206	193	229	182	168	190	198
pH	8.2	10.2	10.1	9.4	9.2	9.8	9.8
Alkalinity (mg/L as $CaCO_3$)	1022	137	107	78	217	167	142
Filtered UV254	0.849	0.815	0.774	0.781	0.79	0.807	0.807
Chlorophyll (ug/L)	4.23	2.57	5.07	2.46	2.51	3.07	2.75
Unfiltered Phycocyanin (ppb)	0	0	1.701	0	0	0	0
Filtered Phycocyanin	4.63	0	0	1.422	0	0	0

(ppb)							
Biomass (g)	\	0.1887	0.2006	0.1956	0.1854	0.1796	0.181
Turbidity (NTU)	0.26	0.91	0.71	0.29	0.33	0.35	0.32

Second Cycle	Initial	Blue		White	
Parameter	Initial OCWD	O1	O2	O1	O2
Silica (mg/L SiO_2)	123	14	11	6	9
Nitrate (mg/L as N)	62.7	52.2	51.8	51.3	51.7
Ammonia (mg/L as N)	8.9	0.4	0.4	0.4	0.5
Orthophosphate(mg/L as PO_4^{3-})	8.3	0.15	0.12	0.12	0.14
Total chemical oxygen demand (mg/L)	128	124	144	136	148
Dissolved chemical oxygen demand (mg/L)	124	120	138	120	140
Calcium hardness (mg/L as $CaCO_3$)	1390	320	300	330	310
Color at 455 nm (PtCo unit)	206	162	164	174	175
pH	8.2	9.5	9.4	10.5	10.2
Alkalinity (mg/L as $CaCO_3$)	1022	210	190	142	137
Filtered UV254	0.849	0.784	0.782	0.777	0.777
Chlorophyll (ug/L)	4.23	1.79	1.67	2.53	1.9
Unfiltered Phycocyanin (ppb)	0	16.54	0	0	0
Filtered Phycocyanin (ppb)	4.63	0	0	0	15
Biomass (g)	\	0.2921	0.2919	0.1963	0.2058
Turbidity (NTU)	0.26	0.34	0.24	2.07	1.25

First Cycle	Initial	Red		Green		Yellow	
Parameter	Initial SAWS	S1	S2	S1	S2	S1	S2
Silica (mg/L SiO_2)	126	18	19	9	11	18.5	12
Nitrate (mg/L as N)	10	2.76	2.68	0.40	0.45	2.82	1.72
Ammonia (mg/L as N)	9.9	0.4	0.4	0.4	0.4	0.4	0.4
Orthophosphate(mg/L as PO_4^{3-})	4.63	0.06	0.06	0.06	0.1	0.12	0.08
Total chemical oxygen demand (mg/L)	40	44	44	56	60	52	68

Dissolved chemical oxygen demand (mg/L)	36	44	44	52	60	60	56
Calcium hardness (mg/L as $CaCO_3$)	890	100	120	100	110	120	110
Color at 455 nm (PtCo unit)	7	45	39	37	41	35	34
pH	8.3	9.7	9.6	10.1	9.9	9.7	9.8
Alkalinity (mg/L as $CaCO_3$)	1488	948	958	968	978	938	958
Filtered UV254	0.124	0.112	0.108	0.112	0.112	0.107	0.108
Chlorophyll (ug/L)	1.339	1.987	2.309	2.054	1.997	1.583	2.018
Unfiltered Phycocyanin (ppb)	10.11	0	0	0	0	0	0
Filtered Phycocyanin (ppb)	0	0	0	0	0	0	0
Biomass (g)	0.0335	\	\	\	\	\	\
Turbidity (NTU)	0.73	0.23	0.25	0.25	0.24	0.19	0.22

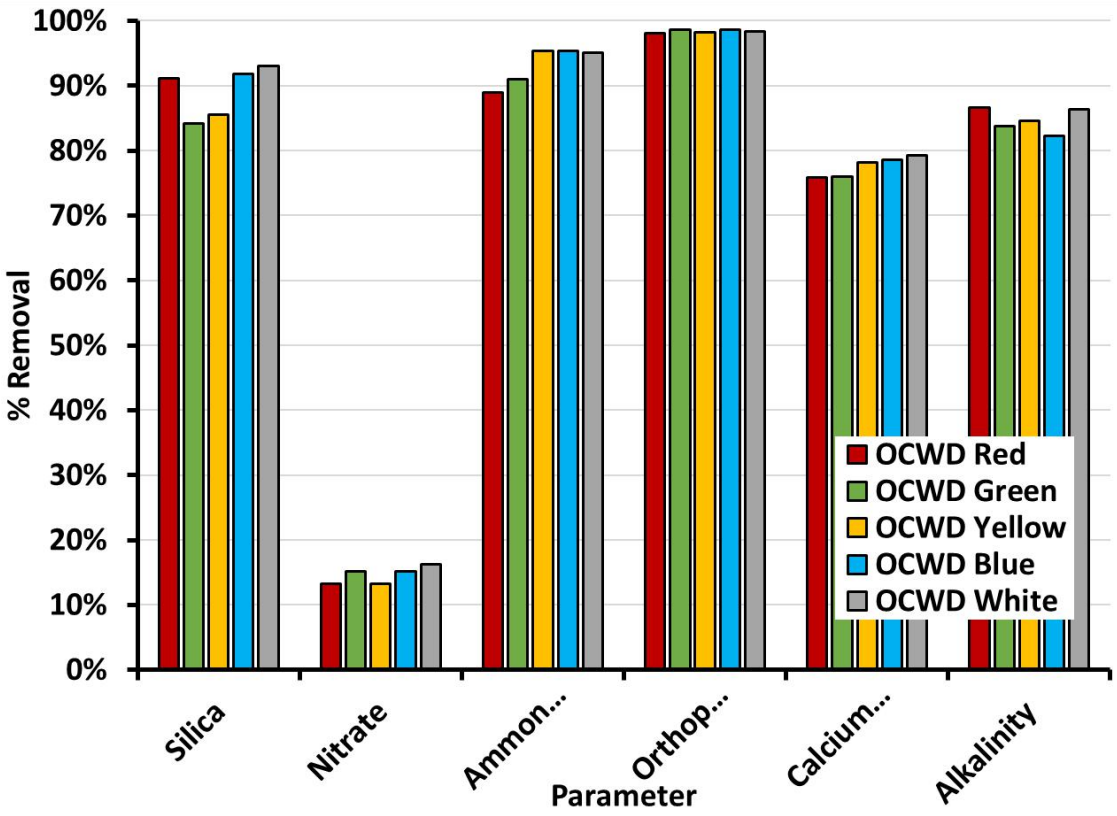
First Cycle	Initial	Blue		White	
Parameter	Initial SAWS	S1	S2	S1	S2
Silica (mg/L SiO_2)	126	5	10	14	10
Nitrate (mg/L as N)	10	0.44	0.66	1.68	0.91
Ammonia (mg/L as N)	9.9	0.4	0.4	0.4	0.4
Orthophosphate(mg/L as PO_4^{3-})	4.63	0.04	0.04	0.08	0.06
Total chemical oxygen demand (mg/L)	40	68	72	56	72
Dissolved chemical oxygen demand (mg/L)	36	54	70	56	52
Calcium hardness (mg/L as $CaCO_3$)	890	130	140	115	110
Color at 455 nm (PtCo unit)	7	34	36	43	32
pH	8.3	10.2	9.9	9.7	10
Alkalinity (mg/L as $CaCO_3$)	1488	957	1027	928	898
Filtered UV254	0.124	0.116	0.117	0.107	0.111
Chlorophyll (ug/L)	0	1.274	1.561	1.168	1.657
Unfiltered Phycocyanin (ppb)	10.11	0	4.282	0	0
Filtered Phycocyanin (ppb)	0	0	0	0	0
Biomass (g)	0.0335	\	\	\	\

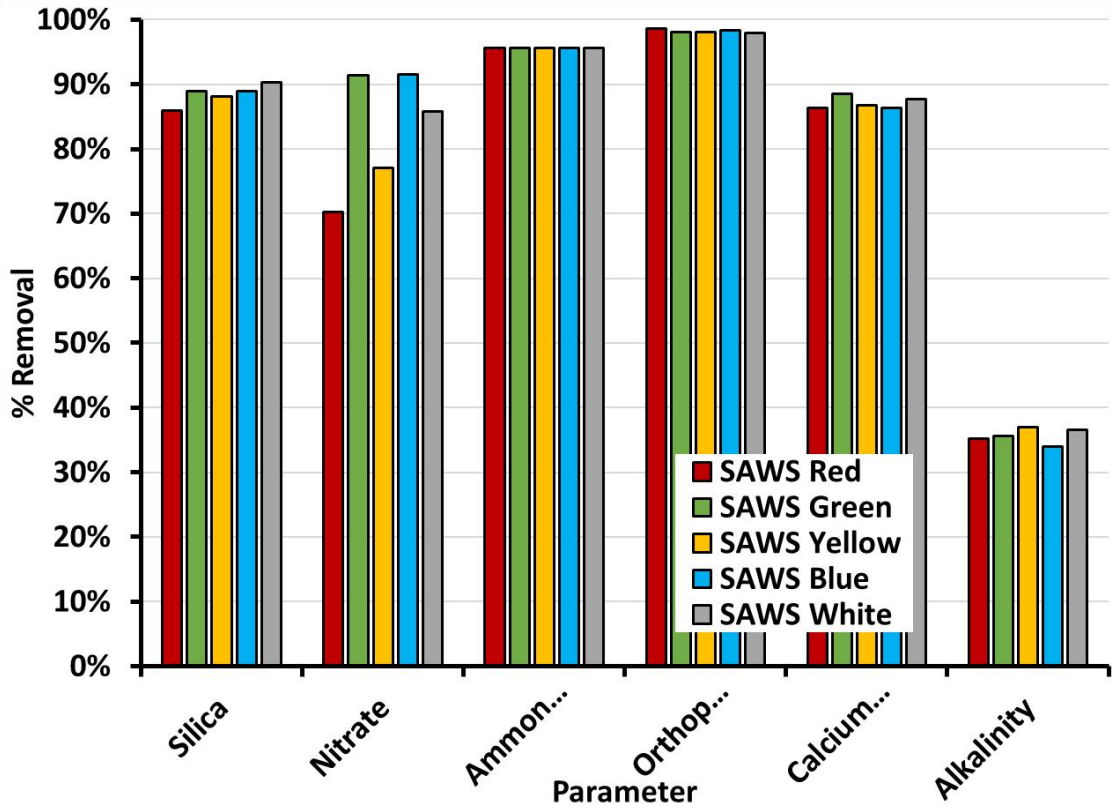
Turbidity (NTU)	0.73	0.24	0.23	0.21	0.23

Second Cycle	Initial	Red		Green		Yellow	
Parameter	Initial SAWS	S1	S2	S1	S2	S1	S2
Silica (mg/L SiO_2)	133	13.5	22.5	18	20	20	11
Nitrate (mg/L as N)	10	2.96	3.51	1	1.62	3.07	1.54
Ammonia (mg/L as N)	8.7	0.4	0.4	0.4	0.4	0.4	0.4
Orthophosphate(mg/L as PO_4^{3-})	4.5	0.06	0.08	0.08	0.1	0.06	0.08
Total chemical oxygen demand (mg/L)	36	60	56	68	64	76	56
Dissolved chemical oxygen demand (mg/L)	28	72	60	68	60	60	64
Calcium hardness (mg/L as $CaCO_3$)	870	125	135	95	100	115	120
Color at 455 nm (PtCo unit)	7	37	40	30	31	47	38
pH	8.1	9.7	9.7	9.9	9.7	9.7	9.9
Alkalinity (mg/L as $CaCO_3$)	1478	988	948	918	958	918	928
Filtered UV254	0.117	0.12	0.117	0.111	0.103	0.114	0.114
Chlorophyll (ug/L)	0.31	2.279	2.053	1.077	1.22	1.048	1.032
Unfiltered Phycocyanin (ppb)	0	0	0	0	0	0	0
Filtered Phycocyanin (ppb)	0	0	0	0	0	0	3.802
Biomass (g)	\	0.124	0.1107	0.1264	0.113	0.1086	0.1129
Turbidity (NTU)	0.03	0.23	0.22	0.26	0.27	0.28	0.27

Second Cycle	Initial	Blue		White	
Parameter	Initial SAWS	S1	S2	S1	S2
Silica (mg/L SiO_2)	133	20	23	13	13
Nitrate (mg/L as N)	10	0.63	1.65	1.70	1.39
Ammonia (mg/L as N)	8.7	0.4	0.4	0.4	0.4
Orthophosphate(mg/L as PO_4^{3-})	4.5	0.14	0.08	0.12	0.12
Total chemical oxygen demand (mg/L)	36	60	72	72	64

Dissolved chemical oxygen demand (mg/L)	28	58	74	76	64
Calcium hardness (mg/L as $CaCO_3$)	870	120	90	110	100
Color at 455 nm (PtCo unit)	7	29	34	38	36
pH	8.1	10	9.8	10	9.9
Alkalinity (mg/L as $CaCO_3$)	1478	960	970	938	998
Filtered UV254	0.117	0.105	0.112	0.117	0.12
Chlorophyll (ug/L)	0.31	0.795	0.742	1.571	2.365
Unfiltered Phycocyanin (ppb)	0	0	0	0	0
Filtered Phycocyanin (ppb)	0	0	0	0	0
Biomass (g)	\	0.1487	0.1436	0.1072	0.1121
Turbidity (NTU)	0.03	0.81	0.27	0.24	0.29

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SAWS Blue
SAWS White
Silica
Nitrate
Ammon...
Orthop...
Calcium...
Alkalinity
Parameter

LIGHT INTENSITIES EXPERIMENT

First Cycle	Initial Bottles		PAR: 200 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	133	109	6	15	6	12
Nitrate (mg/L as N)	63.2	10	58.3	60.3	3.5	3.5
Ammonia (mg/L as N)	9.2	8.5	<0.4	<0.4	0.4	0.4
Orthophosphate(mg/L as PO_4^{3-})	11.4	5	0.07	0.08	0.03	0.04
Total chemical oxygen demand ($mg \cdot L^{-1}$)	120	48	136	152	56	76
Dissolved chemical oxygen demand ($mg \cdot L^{-1}$)[b]	112	52	132	144	52	72
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1610	920	450	495	140	220
Color at 455 nm (PtCo unit)	134	7	133	132	47	37
pH	8.4	8.3	10.9	10	10.8	10.6
Alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	910	920	120	150	360	390
Filtered UV254	0.871	0.143	0.825	0.844	0.111	0.113
Chlorophyll (ug/L)	1.05	0.192	0.41	0.69	2.17	1.295
Unfiltered Phycocyanin (ppb)	11.2	0	9.861	0	2.748	0
Filtered Phycocyanin (ppb)	11.92	0	8.152	5.958	0	4.693
Biomass (g)	0.0164	0.0164	\	\	\	\
Turbidity (NTU)	0.18	0.08	1.51	0.53	0.58	0.2

First Cycle	Initial Bottles		PAR: 310 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	133	109	11	5	7	14
Nitrate (mg/L as N)	63.2	10	58.6	57.7	4.4	4.2
Ammonia (mg/L as N)	9.2	8.5	0.7	0.3	0.7	0.7
Orthophosphate(mg/L as PO_4^{3-})	11.4	5	0.11	0.08	0.18	0.05
Total chemical oxygen demand ($mg \cdot L^{-1}$)	120	48	152	152	56	60

Dissolved chemical oxygen demand (mg·L^{-1})[b]	112	52	132	136	64	60
Calcium hardness (mg·L^{-1} as $CaCO_3$)	1610	920	480	520	130	190
Color at 455 nm (PtCo unit)	134	7	131	130	49	44
pH	8.4	8.3	10.8	10.7	10.8	10.6
Alkalinity (mg·L^{-1} as $CaCO_3$)	910	920	115	60	370	420
Filtered UV254	0.871	0.143	0.809	0.814	0.129	0.14
Chlorophyll (ug/L)	1.05	0.192	0.61	0.74	1.631	2.442
Unfiltered Phycocyanin (ppb)	11.2	0	13.51	12.32	0	0
Filtered Phycocyanin (ppb)	11.92	0	6.248	13.53	0	5.37
Biomass (g)	0.0164	0.0164	\	\	\	\
Turbidity (NTU)	0.18	0.08	1.67	2.35	0.54	0.24

First Cycle	Initial Bottles		PAR: 510 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	133	109	7	11	14	11
Nitrate (mg/L as N)	63.2	10	59.1	60.4	5.2	4.6
Ammonia (mg/L as N)	9.2	8.5	0.5	<0.4	<0.4	0.1
Orthophosphate(mg/L as PO_4^{3-})	11.4	5	0.08	0.06	0.04	0.06
Total chemical oxygen demand (mg·L^{-1})	120	48	148	144	52	68
Dissolved chemical oxygen demand (mg·L^{-1})[b]	112	52	132	136	64	68
Calcium hardness (mg·L^{-1} as $CaCO_3$)	1610	920	500	440	270	190
Color at 455 nm (PtCo unit)	134	7	109	118	45	45
pH	8.4	8.3	10.7	10.4	10.5	11.2
Alkalinity (mg·L^{-1} as $CaCO_3$)	910	920	115	90	490	390
Filtered UV254	0.871	0.143	0.836	0.824	0.118	0.182
Chlorophyll (ug/L)	1.05	0.192	0.69	0.42	2.544	0.505
Unfiltered Phycocyanin (ppb)	11.2	0	5.76	7.981	0	0

Filtered Phycocyanin (ppb)	11.92	0	13.44	2.186	0	0
Biomass (g)	0.0164	0.0164	\	\	\	\
Turbidity (NTU)	0.18	0.08	1.63	0.67	0.42	0.18

Second Cycle	Initial Bottles		PAR: 200 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	124	107	6	9	9	8
Nitrate (mg/L as N)	63	10	57	56.6	5.9	4.5
Ammonia (mg/L as N)	10.2	9.2	0.1	0	0	<0.4
Orthophosphate(mg/L as PO_4^{3-})	11.4	4.65	0.06	0.05	0.03	0.04
Total chemical oxygen demand ($mg \cdot L^{-1}$)	132	52	148	148	68	84
Dissolved chemical oxygen demand ($mg \cdot L^{-1}$)[b]	120	36	140	120	60	64
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1590	960	430	425	280	125
Color at 455 nm (PtCo unit)	130	5	129	146	45	40
pH	8.4	8.6	10.1	10.2	10.4	10.9
Alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	920	930	100	140	610	430
Filtered UV254	0.849	0.138	0.823	0.833	0.129	0.131
Chlorophyll (ug/L)	0.44	0.044	1.6	1.49	0.309	0.905
Unfiltered Phycocyanin (ppb)	18.08	7.027	10.73	18.49	0	2.664
Filtered Phycocyanin (ppb)	12.38	22.22	0	0	0	0
Biomass (g)	\	\	\	\	\	\
Turbidity (NTU)	0.15	0.14	2.76	2.98	0.6	0.17

Second Cycle	Initial Bottles		PAR: 310 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	124	107	3	5	12	10
Nitrate (mg/L as N)	63	10	56.6	56.3	5.6	5.7
Ammonia (mg/L as N)	10.2	9.2	0.4	0	0.2	0.4
Orthophosphate(mg/L as	11.4	4.65	0.16	0.14	0.08	0.2

PO_4^{3-})						
Total chemical oxygen demand ($mg \cdot L^{-1}$)	132	52	144	144	72	72
Dissolved chemical oxygen demand ($mg \cdot L^{-1}$)[b]	120	36	132	124	60	64
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1590	960	510	490	150	120
Color at 455 nm (PtCo unit)	130	5	176	181	46	52
pH	8.4	8.6	10.1	11	10.9	11.2
Alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	920	930	120	140	410	430
Filtered UV254	0.849	0.138	0.833	0.828	0.184	0.202
Chlorophyll (ug/L)	0.44	0.044	1.38	0.63	0.518	0.32
Unfiltered Phycocyanin (ppb)	18.08	7.027	13.23	6.28	0	7.921
Filtered Phycocyanin (ppb)	12.38	22.22	5.647	7.131	0	0
Biomass (g)	\	\	0.294	0.2968	0.1603	0.1745
Turbidity (NTU)	0.15	0.14	5.58	5.66	0.25	0.37

Second Cycle	Initial Bottles		PAR: 510 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	124	107	19	6	7	8
Nitrate (mg/L as N)	63	10	60.5	57	4.5	5.2
Ammonia (mg/L as N)	10.2	9.2	0.4	0.4	0.1	0.4
Orthophosphate(mg/L as PO_4^{3-})	11.4	4.65	0.15	0.06	0.04	0.04
Total chemical oxygen demand ($mg \cdot L^{-1}$)	132	52	142	152	80	68
Dissolved chemical oxygen demand ($mg \cdot L^{-1}$)[b]	120	36	140	124	70	70
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1590	960	515	545	245	330
Color at 455 nm (PtCo unit)	130	5	138	125	46	43
pH	8.4	8.6	10	10.4	10.8	10.6
Alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	920	930	230	365	395	530
Filtered UV254	0.849	0.138	0.871	0.854	0.17	0.133

Chlorophyll (ug/L)	0.44	0.044	1.3	1.21	0.204	0.198
Unfiltered Phycocyanin (ppb)	18.08	7.027	18.6	45.18	0	0
Filtered Phycocyanin (ppb)	12.38	22.22	0	0	0	0
Biomass (g)	\	\	\	\	\	\
Turbidity (NTU)	0.15	0.14	0.6	2.26	0.54	0.52

Third Cycle	Initial Bottles		PAR: 200 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	130	98	20	3	7	5
Nitrate (mg/L as N)	63.4	10	57.8	56.2	7.1	5.7
Ammonia (mg/L as N)	9.4	8.6	0.4	0	0	0.4
Orthophosphate(mg/L as PO_4^{3-})	11.8	5	0.46	0.14	0.1	0.18
Total chemical oxygen demand ($mg \cdot L^{-1}$)	128	44	144	140	80	84
Dissolved chemical oxygen demand ($mg \cdot L^{-1}$)[b]	122	40	120	140	72	64
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1670	900	580	600	240	220
Color at 455 nm (PtCo unit)	131	8	156	154	58	52
pH	8.3	8.7	10.4	10.9	11.6	11
Alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	895	960	200	130	410	430
Filtered UV254	0.847	0.141	0.855	0.82	0.172	0.173
Chlorophyll (ug/L)	1.01	0.684	0.06	0.98	0.59	0.907
Unfiltered Phycocyanin (ppb)	25.81	0	12.64	0	0.054	0
Filtered Phycocyanin (ppb)	12.7	0.282	5.304	0.722	0	0
Biomass (g)	\	\	0.2624	0.2737	0.1348	0.1744
Turbidity (NTU)	0.14	0.14	1.5	3.49	0.68	0.86

Third Cycle	Initial Bottles		PAR: 310 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	130	98	3	5	12	10
Nitrate (mg/L as N)	63.4	10	56.6	56.3	6.5	6.3

Ammonia (mg/L as N)	9.4	8.6	0.4	0	0.2	0.4
Orthophosphate(mg/L as PO_4^{3-})	11.8	5	0.16	0.14	0.08	0.2
Total chemical oxygen demand ($mg \cdot L^{-1}$)	128	44	144	144	72	72
Dissolved chemical oxygen demand ($mg \cdot L^{-1}$)[b]	122	40	132	124	60	64
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1670	900	510	490	150	120
Color at 455 nm (PtCo unit)	131	8	176	181	46	52
pH	8.3	8.7	10.1	11	10.9	11.2
Alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	895	960	120	140	410	430
Filtered UV254	0.847	0.141	0.833	0.828	0.184	0.202
Chlorophyll (ug/L)	1.01	0.684	1.38	0.63	0.518	0.32
Unfiltered Phycocyanin (ppb)	25.81	0	13.23	6.28	0	7.921
Filtered Phycocyanin (ppb)	12.7	0.282	5.647	7.131	0	0
Biomass (g)	\	\	0.294	0.2968	0.1603	0.1745
Turbidity (NTU)	0.14	0.14	5.58	5.66	0.25	0.37

Third Cycle	Initial Bottles		PAR: 510 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	130	98	8	23	8	9
Nitrate (mg/L as N)	63.4	10	56.9	59	5.5	5
Ammonia (mg/L as N)	9.4	8.6	0.1	0.1	0.4	0
Orthophosphate(mg/L as PO_4^{3-})	11.8	5	0.14	0.4	0.3	0.1
Total chemical oxygen demand ($mg \cdot L^{-1}$)	128	44	148	140	88	84
Dissolved chemical oxygen demand ($mg \cdot L^{-1}$)[b]	122	40	124	132	60	76
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1670	900	580	560	130	120
Color at 455 nm (PtCo unit)	131	8	133	145	52	61
pH	8.3	8.7	10.9	10.1	10.9	11.6
Alkalinity ($mg \cdot L^{-1}$ as	895	960	120	120	400	440

$CaCO_3$)						
Filtered UV254	0.847	0.141	0.832	0.866	0.239	0.233
Chlorophyll (ug/L)	1.01	0.684	0.71	1.02	0.639	0.175
Unfiltered Phycocyanin (ppb)	25.81	0	0	0	3.537	0
Filtered Phycocyanin (ppb)	12.7	0.282	1.822	12.84	12.29	0
Biomass (g)	\	\	0.294	0.273	0.1846	0.2012
Turbidity (NTU)	0.14	0.14	2.75	1.08	0.44	0.45

First Cycle	Initial Bottles		PAR: 50 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	129	111	14	20	13	3
Nitrate (mg/L as N)	62.6	10	57.3	57.3	3.5	1.1
Ammonia (mg/L as N)	9.7	8.6	<0.4	< 0.4	< 0.4	<0.4
Orthophosphate(mg/L as PO_4^{3-})	11.5	4.65	0.08	0.12	0.1	0.08
Total chemical oxygen demand ($mg \cdot L^{-1}$)	120	36	128	128	48	52
Dissolved chemical oxygen demand ($mg \cdot L^{-1}$)[b]	132	56	140	144	72	76
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1480	710	350	340	110	80
Color at 455 nm (PtCo unit)	130	23	116	120	29	31
pH	8.6	8.3	9.8	9.7	10.1	10.8
Alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	765	1040	130	120	650	530
Filtered UV254	0.77	0.088	0.762	0.763	0.094	0.102
Chlorophyll (ug/L)	3.3	0.531	2.66	3.26	4.175	1.818
Unfiltered Phycocyanin (ppb)	10.24	0	25.88	23.88	0	0
Filtered Phycocyanin (ppb)	29.99	0	5.773	0	0	11.67
Biomass (g)	0.025	0.025	\	\	\	\
Turbidity (NTU)	0.27	0.25	0.81	0.52	0.51	0.25

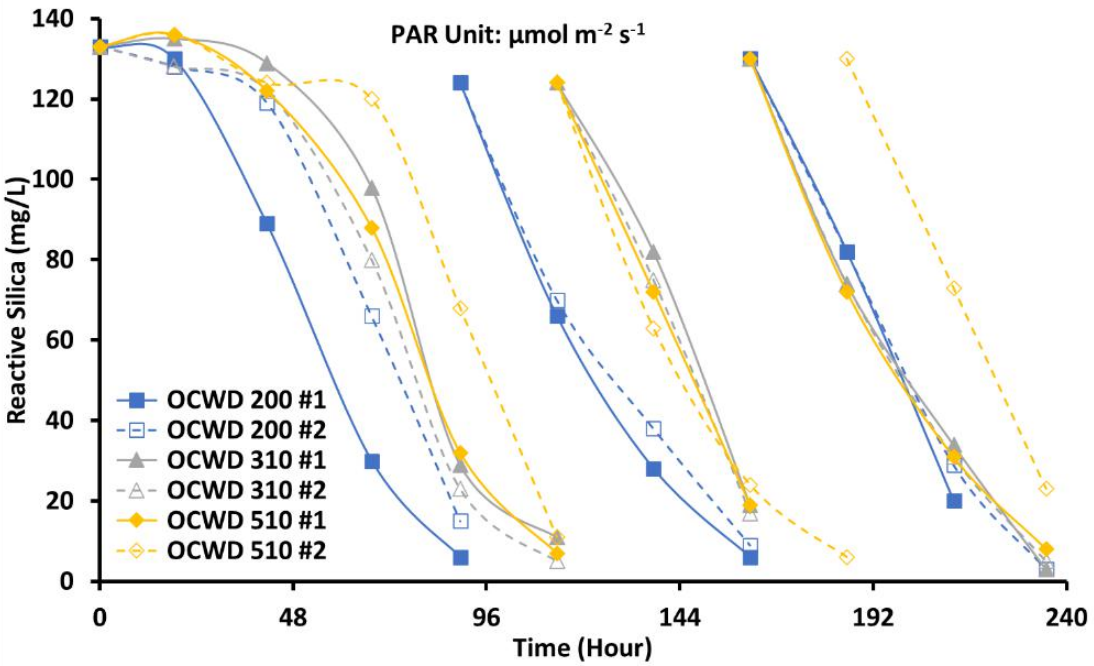
First Cycle	Initial Bottles		PAR: 100 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	129	111	18	15	5	7
Nitrate (mg/L as N)	62.6	10	58.5	57.3	2.0	1.8
Ammonia (mg/L as N)	9.7	8.6	<0.4	<0.4	<0.4	<0.4
Orthophosphate(mg/L as PO_4^{3-})	11.5	4.65	0.16	0.1	0.06	0.06
Total chemical oxygen demand ($mg \cdot L^{-1}$)	120	36	124	132	56	60
Dissolved chemical oxygen demand ($mg \cdot L^{-1}$)[b]	132	56	144	144	76	60
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1480	710	390	390	210	130
Color at 455 nm (PtCo unit)	130	23	124	119	47	43
pH	8.6	8.3	10.3	9.6	11.2	11.3
Alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	765	1040	130	120	500	455
Filtered UV254	0.77	0.088	0.775	0.779	0.117	0.12
Chlorophyll (ug/L)	3.3	0.531	2.32	2.68	2.595	2.179
Unfiltered Phycocyanin (ppb)	10.24	0	0.932	0	0	0
Filtered Phycocyanin (ppb)	29.99	0	0	0	0	6.801
Biomass (g)	0.025	0.025	\	\	\	\
Turbidity (NTU)	0.27	0.25	0.71	0.6	1.09	0.45

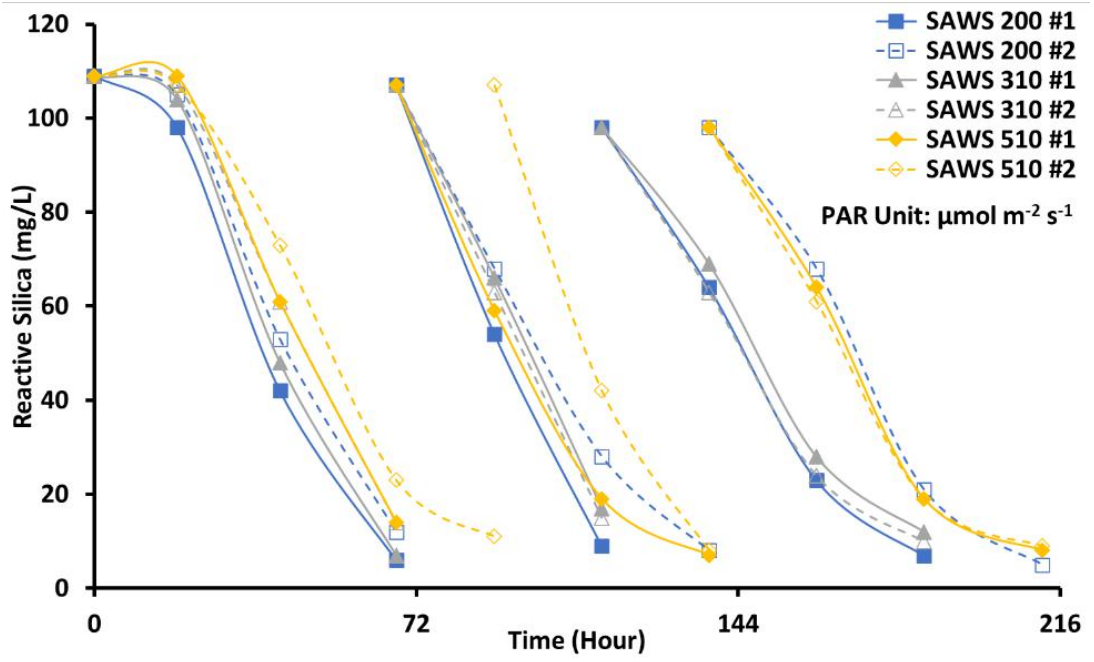
Second Cycle	Initial Bottles		PAR: 50 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	132	110	19	18	3	17
Nitrate (mg/L as N)	63.5	10	56.4	56.3	1.9	3.8
Ammonia (mg/L as N)	9.7	8.3	< 0.4	< 0.4	< 0.4	< 0.4
Orthophosphate(mg/L as PO_4^{3-})	11.8	4.53	0.16	0.08	0.1	0.1
Total chemical oxygen demand ($mg \cdot L^{-1}$)	116	28	120	124	52	48
Dissolved chemical oxygen demand ($mg \cdot L^{-}$	120	44	140	136	72	72

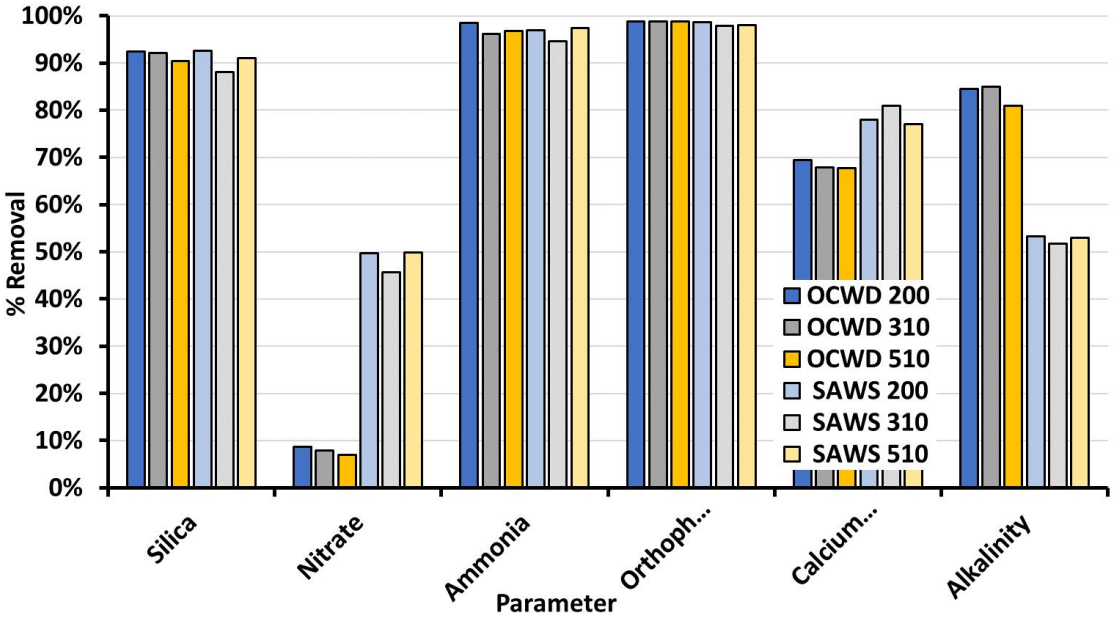
$^{1})^{b}$						
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1580	750	440	430	80	160
Color at 455 nm (PtCo unit)	131	9	116	122	33	27
pH	8.3	9	10.1	10.2	10.6	10
Alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	980	1045	150	140	490	595
Filtered UV254	0.732	0.095	0.744	0.75	0.1	0.091
Chlorophyll (ug/L)	2.91	1.206	1.79	2.46	3.165	1.761
Unfiltered Phycocyanin (ppb)	12.87	0	0	0	3.451	0
Filtered Phycocyanin (ppb)	21.28	0	2.833	0	0	0
Biomass (g)	\	\	0.1886	0.2098	0.108	0.1367
Turbidity (NTU)	0.18	0.09	0.96	1.29	0.28	0.2

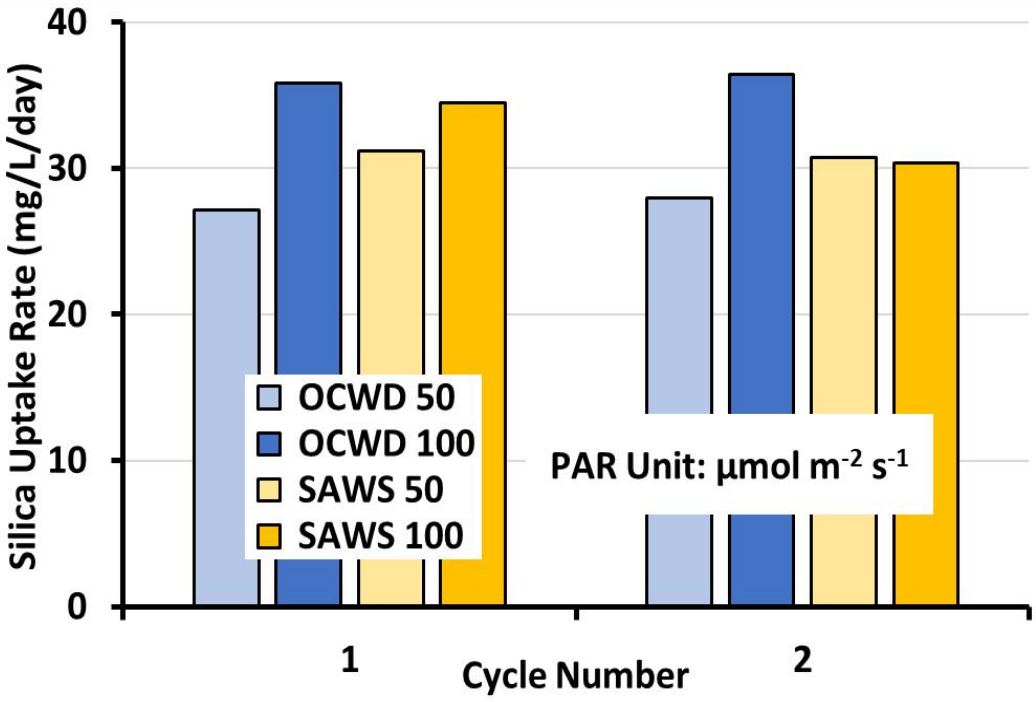
Second Cycle	Initial Bottles		PAR: 100 µmol m^{-2} s^{-1}			
Parameter	Initial OCWD	Initial SAWS	OCWD #1	OCWD #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	132	110	4	3	6	8
Nitrate (mg/L as N)	63.5	10	56.6	56	3.1	2.9
Ammonia (mg/L as N)	9.7	8.3	< 0.4	< 0.4	< 0.4	< 0.4
Orthophosphate(mg/L as PO_4^{3-})	11.8	4.53	0.08	0.04	0.1	0.08
Total chemical oxygen demand ($mg \cdot L^{-1}$)	116	28	132	132	68	68
Dissolved chemical oxygen demand ($mg \cdot L^{-1}$)^{b}	120	44	144	140	84	80
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1580	750	440	430	110	120
Color at 455 nm (PtCo unit)	131	9	124	115	40	36
pH	8.3	9	10.3	9.8	10.8	11.1
Alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	980	1045	115	105	480	475
Filtered UV254	0.732	0.095	0.749	0.758	0.132	0.133
Chlorophyll (ug/L)	2.91	1.206	2.22	2.33	1.793	1.639
Unfiltered Phycocyanin (ppb)	12.87	0	0	0	0	0
Filtered Phycocyanin	21.28	0	0	0	0	0

(ppb)						
Biomass (g)	\	\	0.2001	0.2044	0.1329	0.1299
Turbidity (NTU)	0.18	0.09	2.07	1.69	0.2	0.2






100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Removal
OCWD 200
OCWD 310
OCWD 510
SAWS 200
SAWS 310
SAWS 510
Silica
Nitrate
Ammonia
Orthoph...
Calcium...
Alkalinity
Parameter


40
30
20
10
0
Silica Uptake Rate (mg/L/day)
OCWD 50
OCWD 100
SAWS 50
SAWS 100
PAR Unit: µmol m-2 s-1
1
2
Cycle Number

INTERMITTENT & CONTINUOUS LIGHT EXPERIMENT

First Cycle	Initial		Intermittent Light				Continuous Light			
Parameter	OCWD	SAWS	O1	O2	S1	S2	O1	O2	S1	S2
Silica (mg/L SiO_2)	128	103	14	16	7	13	5	14	7	11
Nitrate (mg/L as N)	63.2	10	61	60.7	3.3	3.7	59.1	61.2	2.5	2.7
Ammonia (mg/L as N)	10.2	8.8	0	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
Orthophosphate (mg/L as PO_4^{3-})	11.6	4.67	0.1	0.1	0.04	0.06	0.24	0.08	0.1	0.06
Total chemical oxygen demand (mg/L)	120	24	124	144	52	44	140	140	70	36
Dissolved chemical oxygen demand (mg/L)	112	24	132	132	60	52	140	112	76	52
Calcium hardness (mg/L as $CaCO_3$)	1680	750	440	420	190	230	440	440	80	70
Color at 455 nm (PtCo unit)	133	2	117	119	34	32	132	121	47	52
pH	8.2	8.4	9.3	9.4	9.5	9.4	9.8	9.4	10.4	10.5
Alkalinity (mg/L as $CaCO_3$)	1050	1030	160	160	600	590	170	170	430	480
Filtered UV254	0.811	0.074	0.773	0.787	0.108	0.101	0.775	0.772	0.143	0.144
Chlorophyll (ug/L)	1.76	0.218	0.89	0.32	0.398	1.414	0.8	0.79	0.639	0.787
Unfiltered Phycocyanin (ppb)	1.772	0	0	0	0	11.81	0	14.47	0	0
Filtered	0	0	0	13.7	0	0	0	4.59	0	0

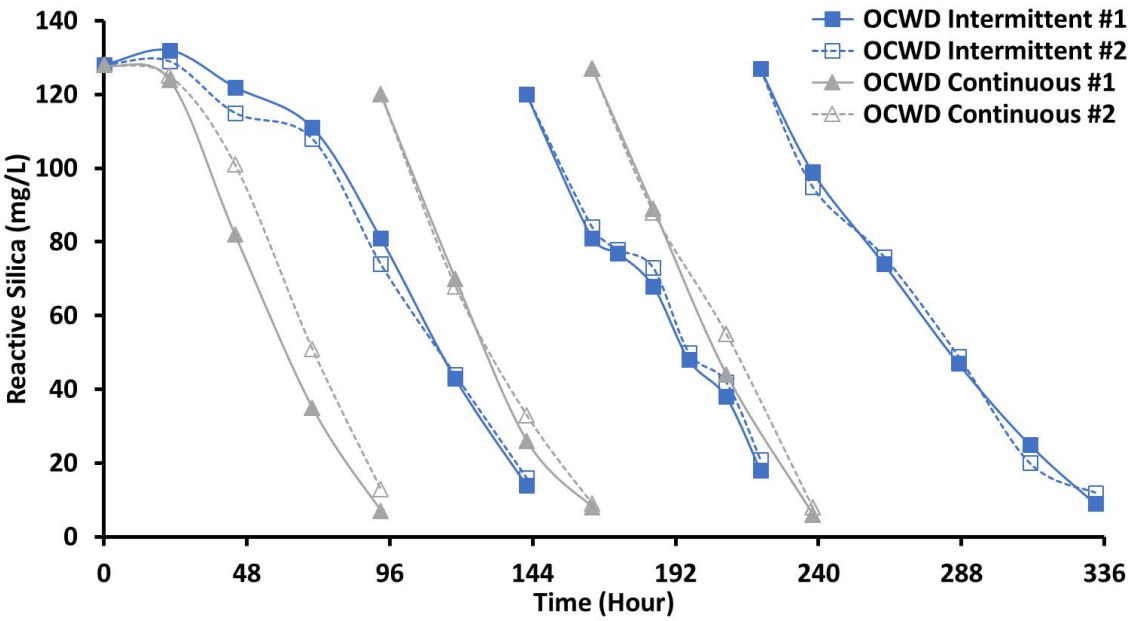
Phycocyanin (ppb)				6				2		
Biomass (g)	0.0286	0.0213	\	\	\	\	\	\	\	\
Turbidity (NTU)	0.62	0.18	0.39	0.37	0.39	0.21	1.8	0.77	0.21	0.22

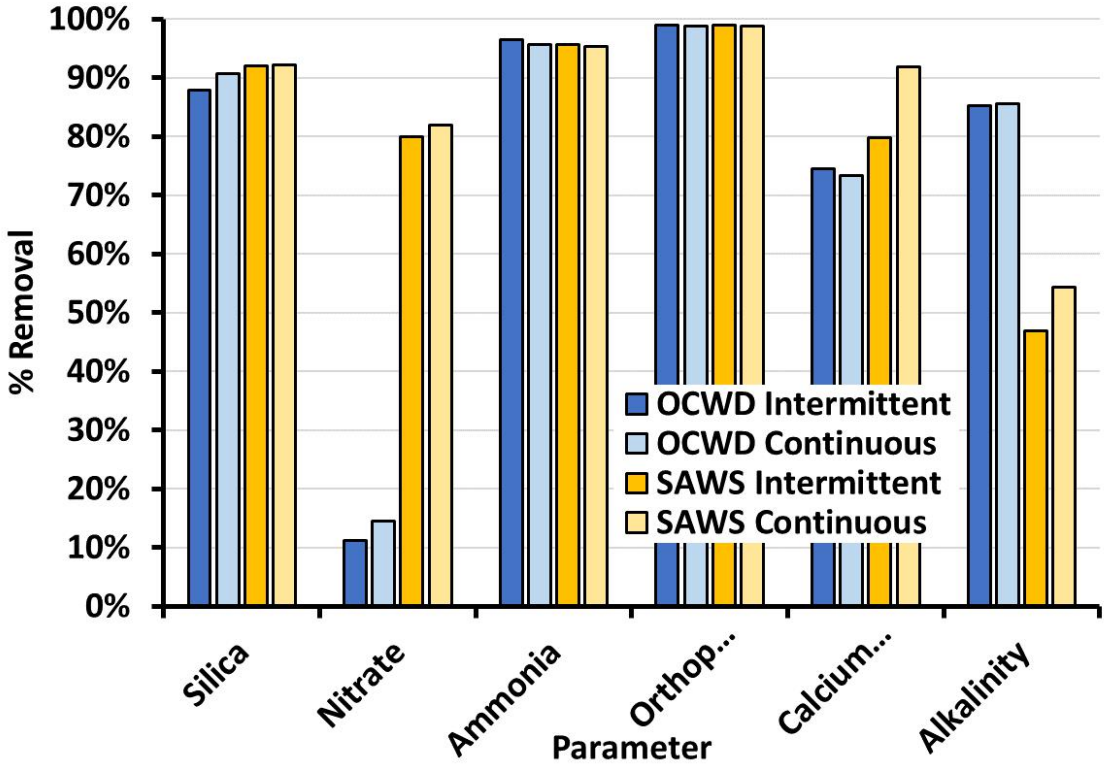
Second Cycle	Initial		Intermittent Light				Continuous Light			
Parameter	OCWD	SAWS	O1	O2	S1	S2	O1	O2	S1	S2
Silica (mg/L SiO_2)	120	100	18	21	8	9	10	18	9	9
Nitrate (mg/L as N)	64.9	10	57	57.9	2.7	1.6	41.4	51.6	2.7	2.2
Ammonia (mg/L as N)	10.2	9.1	<0.4	<0.4	<0.4	<0.4	<0.4	0.5	<0.4	0.6
Orthophosphate (mg/L as PO_4^{3-})	11.7	5	0.16	0.14	0.06	0.08	0.2	0.12	0.1	0.06
Total chemical oxygen demand (mg/L)	116	12	116	124	44	40	132	120	48	56
Dissolved chemical oxygen demand (mg/L)	100	20	128	140	52	56	148	140	76	84
Calcium hardness (mg/L as $CaCO_3$)	1670	690	420	400	190	170	440	460	60	70
Color at 455 nm (PtCo unit)	121	5	117	114	25	35	125	124	38	34
pH	8	8.5	9.4	8.4	9.9	9.9	9.8	10.2	10.7	10.7
Alkalinity (mg/L as $CaCO_3$)	837	1042	137	132	557	552	122	127	482	467
Filtered UV254	0.816	0.077	0.776	0.774	0.104	0.105	0.8	0.786	0.153	0.157
Chlorophyll (ug/L)	1.25	0.254	0.95	0.84	0.468	0.015	0.16	0.35	0.015	0.605
Unfiltered	0	0	0	0	0	0	0	0	0	0

Phycocyanin (ppb)										
Filtered Phycocyanin (ppb)	0	0	0	0	0	0	14.45	0	1.211	0
Biomass (g)	\	\	\	\	\	\	\	\	\	\
Turbidity (NTU)	0.54	0.63	0.43	0.67	0.29	1.13	1.94	1.3	0.27	0.4

Third Cycle	Initial		Intermittent Light				Continuous Light			
Parameter	OCWD	SAWS	O1	O2	S1	S2	O1	O2	S1	S2
Silica (mg/L SiO_2)	127	102	9	12	6	8	8	15	8	6
Nitrate (mg/L as N)	65	10	52.8	53.5	2.2	2.5	58.5	57.9	2.2	2.5
Ammonia (mg/L as N)	10.5	9	0.6	0.4	0.5	0.4	0.6	0.4	0.4	0.4
Orthophosphate (mg/L as PO_4^{3-})	11.5	4.56	0.14	0.12	0.08	0.08	0.1	0.1	0.06	0.06
Total chemical oxygen demand ($mg \cdot L^{-1}$)	108	20	124	132	52	40	132	120	56	72
Dissolved chemical oxygen demand ($mg \cdot L^{-1}$)[b]	112	16	124	132	52	56	136	136	76	88
Calcium hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	1630	650	440	420	110	110	420	450	80	90
Color at 455 nm (PtCo unit)	131	3	140	131	36	37	129	126	41	50
pH	8.3	8.5	9.8	9.8	9.8	9.7	9.9	10.1	10.8	10.5
Alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	967	1047	132	117	447	487	107	127	457	462
Filtered UV254	0.798	0.081	0.801	0.802	0.113	0.112	0.793	0.798	0.164	0.167
Chlorophyll (ug/L)	3.31	0.145	2.36	2.95	1.35	2.182	2.06	2.03	1.473	1.849
Unfiltered Phycocyanin (ppb)	0.862	0	0	19.47	0	0	0	0	0	0
Filtered	5.76	0	0	0	0	0	0	0	0	0

Phycocyanin (ppb)	2									
Biomass (g)	\	\	0.3208	0.3128	0.1614	0.2315	0.3467	0.3414	0.2118	0.2448
Turbidity (NTU)	0.23	0.17	2.15	0.46	0.24	0.17	1.1	0.75	0.26	0.4




100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Removal
OCWD Intermittent
OCWD Continuous
SAWS Intermittent
SAWS Continuous
Silica
Nitrate
Ammonia
Orthop...
Calcium...
Alkalinity
Parameter

INCUBATION TEMPERATURES EXPERIMENT

First Cycle	Initial	Incubation Temperature: 10 °C		Incubation Temperature: 23 °C	
Parameter	Initial OCWD	OCWD #1	OCWD #2	OCWD #1	OCWD #2
Silica (mg/L SiO_2)	133	9	15	5	8
Nitrate (mg/L as N)	60.8	55.8	56.3	52.7	48.5
Ammonia (mg/L as N)	8	<0.4	<0.4	<0.4	<0.4
Orthophosphate (mg/L as PO_4^{3-})	8.1	0.04	0.06	0.06	0.04
Total chemical oxygen demand (mg/L)	140	144	148	160	184
Dissolved chemical oxygen demand (mg/L)	128	132	136	144	172
Calcium hardness (mg/L as $CaCO_3$)	1480	360	380	280	320
Color at 455 nm (PtCo unit)	206	171	168	172	112
pH	8.2	9	9.1	9.8	10
Alkalinity (mg/L as $CaCO_3$)	976	256	266	186	166
Filtered UV254	0.886	0.82	0.784	0.809	0.56
Chlorophyll (ug/L)	1.83	0.93	1.19	1.43	0.81
Unfiltered Phycocyanin (ppb)	0	0	0	0	0
Filtered Phycocyanin (ppb)	0	0	0	0	0
Biomass (g)	0.0284	0.1756	0.167	\	\
Turbidity (NTU)	0.27	0.4	2.1	2.12	0.42

First Cycle	Initial	Incubation Temperature: 30 °C		Incubation Temperature: 40 °C	
Parameter	Initial OCWD	OCWD #1	OCWD #2	OCWD #1	OCWD #2
Silica (mg/L SiO_2)	133	14	16	140	146
Nitrate (mg/L as N)	60.8	39.2	52.8	62.7	62.5
Ammonia (mg/L as N)	8	0.4	0.4	6.8	6.9
Orthophosphate (mg/L as PO_4^{3-})	8.1	0.06	0.14	2.64	2.62
Total chemical oxygen demand (mg/L)	140	176	152	188	192
Dissolved chemical oxygen demand (mg/L)	128	164	144	168	176

Calcium hardness (mg/L as $CaCO_3$)	1480	300	310	830	810
Color at 455 nm (PtCo unit)	206	106	173	138	138
pH	8.2	10	10.1	8.2	8.3
Alkalinity (mg/L as $CaCO_3$)	976	106	176	656	736
Filtered UV254	0.886	0.59	0.784	0.89	0.902
Chlorophyll (ug/L)	1.83	0.95	2.15	1.09	0.65
Unfiltered Phycocyanin (ppb)	0	0	21.06	0	0
Filtered Phycocyanin (ppb)	0	0	0	0	0
Biomass (g)	0.0284	\	\	0.0528	0.0495
Turbidity (NTU)	0.27	0.79	1.11	1.42	1.41

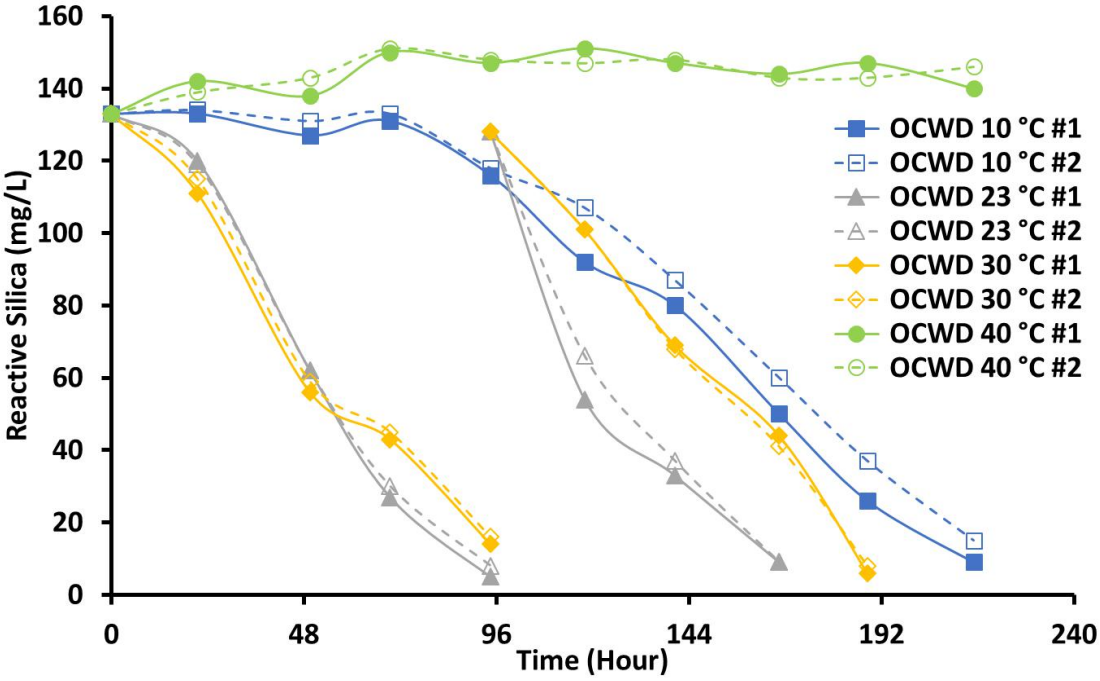
Second Cycle	Initial	Incubation Temperature: 23 °C		Incubation Temperature: 30 °C	
Parameter	Initial OCWD	OCWD #1	OCWD #2	OCWD #1	OCWD #2
Silica (mg/L SiO_2)	128	9	9	6	8
Nitrate (mg/L as N)	63.2	52.3	43.7	51.8	51.9
Ammonia (mg/L as N)	8.3	<0.4	<0.4	<0.4	<0.4
Orthophosphate (mg/L as PO_4^{3-})	8.2	0.04	0.05	0.15	0.06
Total chemical oxygen demand (mg/L)	144	156	180	172	176
Dissolved chemical oxygen demand (mg/L)	124	152	168	156	152
Calcium hardness (mg/L as $CaCO_3$)	1710	380	390	310	320
Color at 455 nm (PtCo unit)	211	193	131	160	215
pH	8.3	10.3	10.3	10.1	10.2
Alkalinity (mg/L as $CaCO_3$)	1216	166	166	246	216
Filtered UV254	0.877	0.83	0.672	0.801	0.861
Chlorophyll (ug/L)	1.65	1.52	0.93	2.37	2.7
Unfiltered Phycocyanin (ppb)	0	0	0	0	0
Filtered Phycocyanin (ppb)	0	0	0	0	0
Biomass (g)	\	0.3019	0.2986	0.2565	0.256
Turbidity (NTU)	0.29	3.29	1.19	2.88	5.9

First Cycle	Initial	Incubation Temperature: 10 °C		Incubation Temperature: 23 °C	
Parameter	Initial SAWS	SAWS #1	SAWS #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	132	10	14	6	7
Nitrate (mg/L as N)	10	4.8	5.1	1.9	1.7
Ammonia (mg/L as N)	8.2	0.4	0.4	0.4	0.4
Orthophosphate (mg/L as PO_4^{3-})	4.42	0.12	0.14	0.15	0.11
Total chemical oxygen demand (mg/L)	48	64	64	88	84
Dissolved chemical oxygen demand (mg/L)	28	52	60	88	72
Calcium hardness (mg/L as $CaCO_3$)	610	80	90	60	50
Color at 455 nm (PtCo unit)	4	52	53	61	63
pH	8.1	10.2	10	10.5	10.4
Alkalinity (mg/L as $CaCO_3$)	1426	976	1016	896	936
Filtered UV254	0.119	0.157	0.161	0.227	0.218
Chlorophyll (ug/L)	0.401	0.492	0.083	0.275	0.74
Unfiltered Phycocyanin (ppb)	0	0	0	0	0
Filtered Phycocyanin (ppb)	0	0	9.657	0	0
Biomass (g)	0.02875	0.0896	0.0899	\	\
Turbidity (NTU)	0.06	0.37	0.44	0.97	1.05

First Cycle	Initial	Incubation Temperature: 30 °C		Incubation Temperature: 40 °C	
Parameter	Initial SAWS	SAWS #1	SAWS #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	132	13	14	156	157
Nitrate (mg/L as N)	10	3.6	3.4	10.5	10.3
Ammonia (mg/L as N)	8.2	0.4	0.4	7.2	7.7
Orthophosphate (mg/L as PO_4^{3-})	4.42	0.02	0.03	5.6	5.65
Total chemical oxygen demand (mg/L)	48	60	72	108	96
Dissolved chemical oxygen demand (mg/L)	28	56	56	92	76
Calcium hardness (mg/L as $CaCO_3$)	610	90	90	565	560

Color at 455 nm (PtCo unit)	4	60	57	76	102
pH	8.1	9.9	9.8	8.8	8.4
Alkalinity (mg/L as $CaCO_3$)	1426	936	956	1376	1436
Filtered UV254	0.119	0.153	0.148	0.274	0.261
Chlorophyll (ug/L)	0.401	1.59	3.357	1.171	0.945
Unfiltered Phycocyanin (ppb)	0	0	0	0	0
Filtered Phycocyanin (ppb)	0	0	0	0	0
Biomass (g)	0.02875	\	\	0.0234	0.0232
Turbidity (NTU)	0.06	0.82	0.86	3.5	5.76

Second Cycle	Initial	Incubation Temperature: 23 °C		Incubation Temperature: 30 °C	
Parameter	Initial SAWS	SAWS #1	SAWS #2	SAWS #1	SAWS #2
Silica (mg/L SiO_2)	133	10	19	9	8
Nitrate (mg/L as N)	10	3.9	5.1	1.2	1.5
Ammonia (mg/L as N)	9.2	0.3	0.1	0.3	0.4
Orthophosphate (mg/L as PO_4^{3-})	4.46	0.12	0.16	0.24	0.26
Total chemical oxygen demand (mg/L)	28	68	76	88	84
Dissolved chemical oxygen demand (mg/L)	28	64	64	76	84
Calcium hardness (mg/L as $CaCO_3$)	660	105	115	65	60
Color at 455 nm (PtCo unit)	8	44	40	89	88
pH	8.3	9.9	9.6	10.5	10.6
Alkalinity (mg/L as $CaCO_3$)	1446	966	966	866	916
Filtered UV254	0.119	0.146	0.139	0.223	0.219
Chlorophyll (ug/L)	0.195	1.13	1.731	4.63	5.31
Unfiltered Phycocyanin (ppb)	0	0	0	0	0
Filtered Phycocyanin (ppb)	0	0	0	0	0
Biomass (g)	\	0.1732	0.1471	0.1433	0.1388
Turbidity (NTU)	0.1	0.41	0.31	1.55	1.7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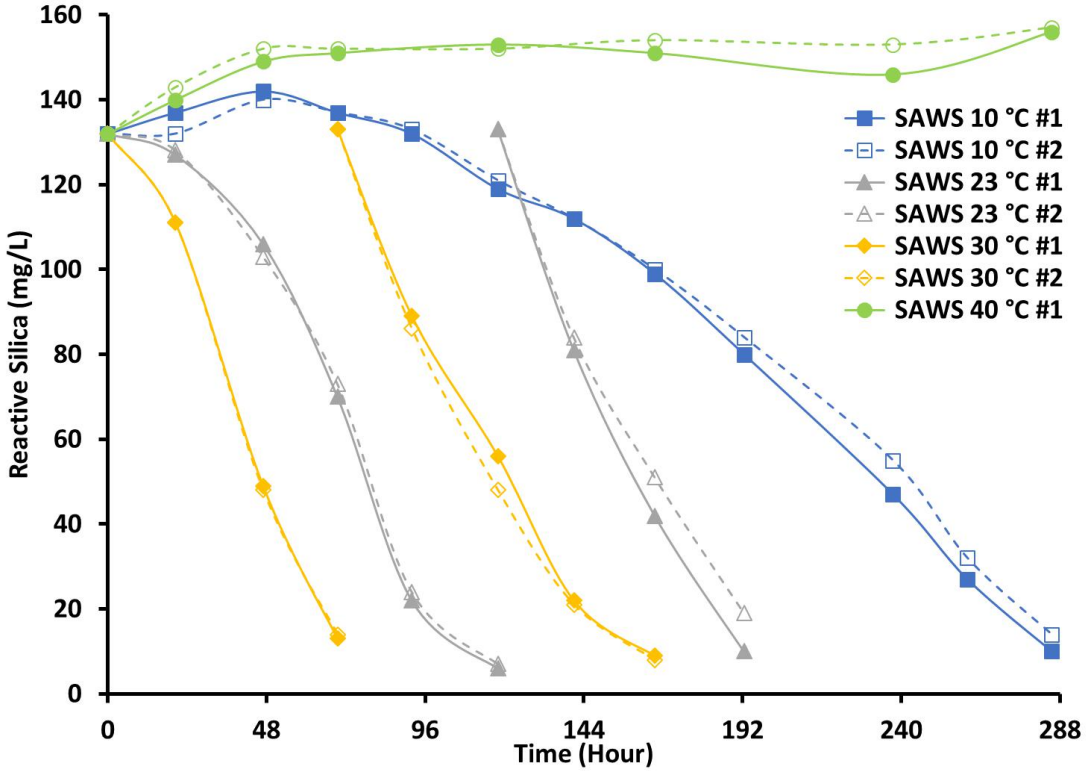
60
80
100
120
140
160
0
48
96
144
192
240
OCWD 10 °C #1
OCWD 10 °C #2
OCWD 23 °C #1
OCWD 23 °C #2
OCWD 30 °C #1
OCWD 30 °C #2
OCWD 40 °C #1
OCWD 40 °C #2


Reactive Silica (mg/L)
Time (Hour)
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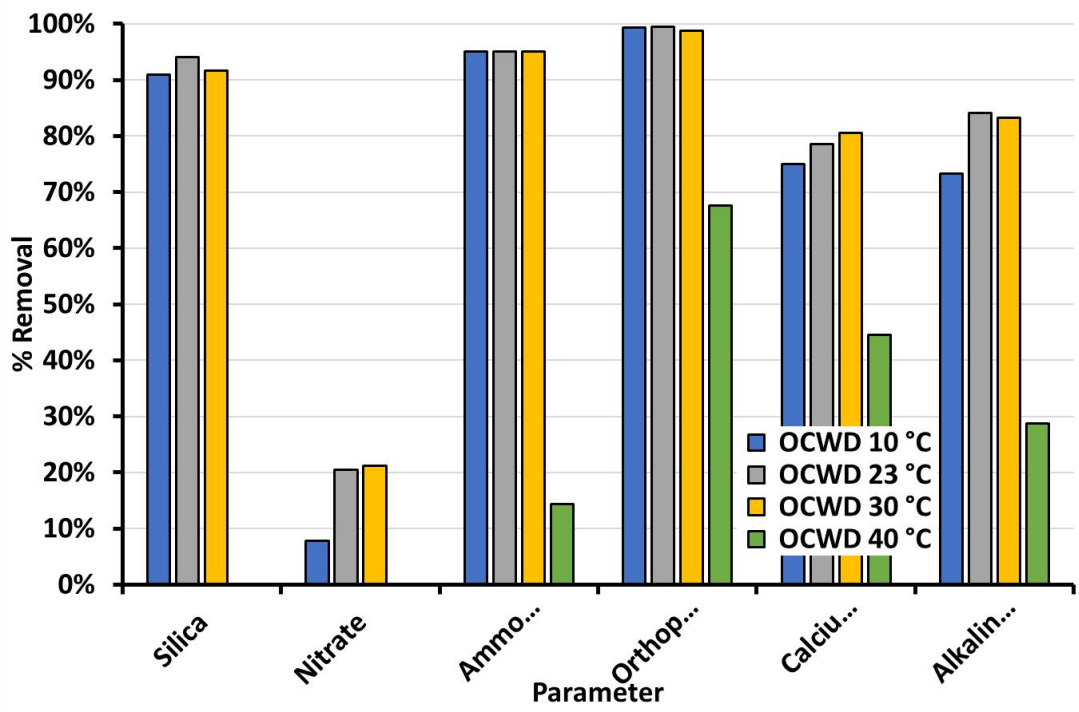
40
60
80
100
120
140
160
0
48
96
144
192
240
288
SAWS 10 °C #1
SAWS 10 °C #2
SAWS 23 °C #1
SAWS 23 °C #2
SAWS 30 °C #1
SAWS 30 °C #2
SAWS 40 °C #1


100%
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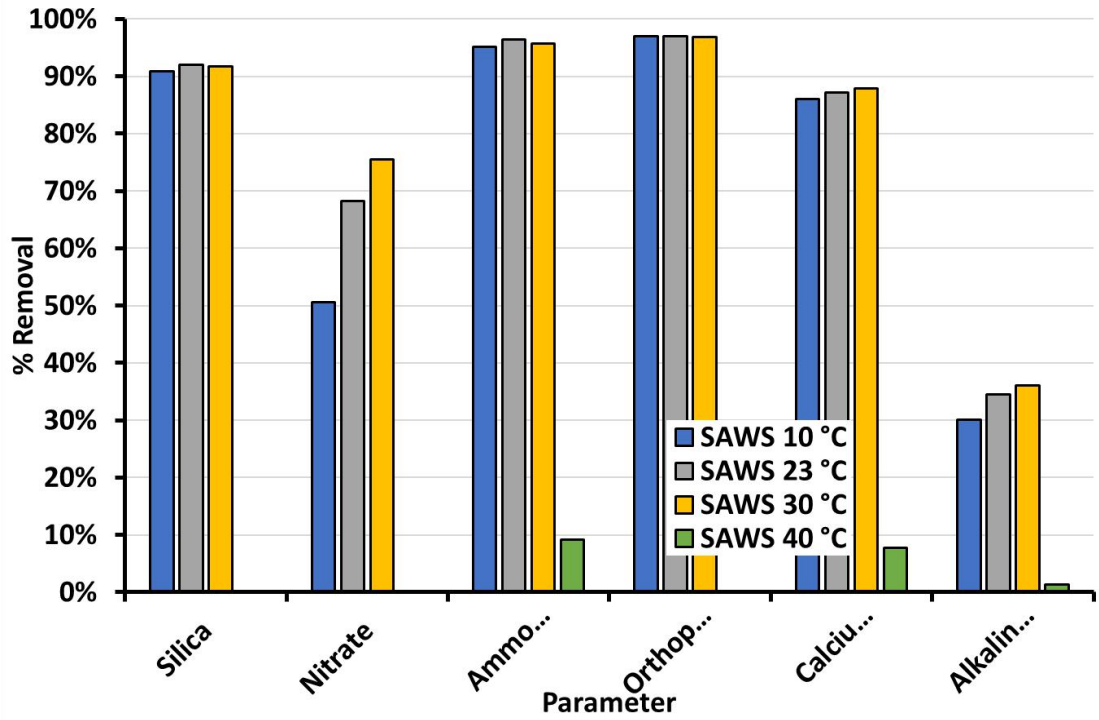
10%
0%
% Removal
OCWD 10 °C
OCWD 23 °C
OCWD 30 °C
OCWD 40 °C
Silica
Nitrate
Ammo...
Orthop...
Calciu...
Alkalin...
Parameter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% Removal
SAWS 10 °C
SAWS 23 °C
SAWS 30 °C
SAWS 40 °C
Silica
Nitrate
Ammo...
Orthop...
Calciu...
Alkalin...
Parameter

ABILENE HAMBY WRF & EL PASO KBHDP ROCS

Parameters	Abilene Hamby WRF	El Paso KBHDP	OCWD CCRO	WBMWD ECLWRF
Calcium (mg/L)	529	873	950	367
Magnesium (mg/L)	1010	290	927	493
Iron (mg/L)	0.14	0.08	<0.02	0.27
Ammonia-N (mg/L)	3.7	N/A	0.46	152
Chloride (mg/L)	1,644	6,997	3,444	1,244
Sulfate (mg/L)	1,280	1,360	2,100	1,300
Bicarbonate (mg/L)	507	244	1120	631
Nitrate-N (mg/L)	82.7	<0.23	112	2.08
Reactive silica (mg/L)	55.5	129.7	92.75	98.7
Orthophosphate (mg/L)	1.48	0.32	16.55	65.5
TDS (mg/L)	5,246	12,080	8,904	3,893
Total hardness (mg/L as $CaCO_3$)	2,330	2,470	3,300	1,410
Calcium hardness (mg/L as $CaCO_3$)	1,320	2,180	2,373	918
Alkalinity (mg/L as $CaCO_3$)	831	401	1836.5	1035
Total chemical oxygen demand (mg/L)	167	54	228	184
Dissolved chemical oxygen demand (mg/L)	158	69	208	180
pH	7.1	7.9	7.6	7.2
Color at 455 nm (PtCo unit)	108	<5	354	230
Conductivity (mS/cm)	7.83	18.03	13.3	5.8

Cycle No.	First Cycle					
Parameter	Initial Hamby	Initial KBH	Hamby #1	Hamby #2	KBH #1	KBH #2
Silica (mg/L SiO_2)	43.5	80.1	2.1	2.5	<1	<1
Nitrate (mg/L as N)	82.15	10	76.4	76.7	4.8	3.4
Ammonia (mg/L as N)	6.4	0.35	<0.4	<0.4	<0.4	<0.4
Orthophosphate (mg/L as	5.93	3.43	0.08	0.07	0.10	0.07

PO_4^{3-})						
Total chemical oxygen demand (mg/L)	162	70	148	152	90	80
pH	8.6	8.6	10.1	9.9	10.3	10.0
Color at 455 nm (PtCo unit)	103	5	111	111	20	19
Filtered UV_{254} (OD)	0.894	0.027	0.890	0.881	0.066	0.066
Calcium hardness (mg/L as $CaCO_3$)	1,330	1,735	680	620	1,395	1,395
Alkalinity (mg/L as $CaCO_3$)	839	409	130	130	110	90
Biomass (g/L)	0.375	0.375	X	X	X	X

Cycle No.	Second Cycle					
Parameter	Initial Hamby	Initial KBH	Hamby #1	Hamby #2	KBH #1	KBH #2
Silica (mg/L SiO_2)	48	78	4	3.2	11	4.5
Nitrate (mg/L as N)	81.10	10	74.55	77.1	5.5	6.5
Ammonia (mg/L as N)	6.2	X	<0.4	<0.4	<0.4	<0.4
Orthophosphate (mg/L as PO_4^{3-})	5.90	3.28	0.13	0.38	0.13	0.07
Total chemical oxygen demand (mg/L)	170	74	156	152	60	68
pH	8.8	8.8	9.9	9.8	10.5	8.7
Color at 455 nm (PtCo unit)	98	<5	111	110	23	22
Filtered UV_{254} (OD)	0.896	0.014	0.899	0.885	0.048	0.062
Calcium hardness (mg/L as $CaCO_3$)	1,420	1,715	645	655	1,345	1,380
Alkalinity (mg/L as	780	390	130	190	90	80

$CaCO_3$)						
Biomass (g/L)	X	X	X	X	X	X

Cycle No.	Third Cycle					
Parameter	Initial Hamby	Initial KBH	Hamby #1	Hamby #2	KBH #1	KBH #2
Silica (mg/L SiO_2)	45	85	2.7	1.1	13.25	48.5
Nitrate (mg/L as N)	81.9	10	76.4	76.75	5.4	4.6
Ammonia (mg/L as N)	6.3	X	<0.4	<0.4	X	X
Orthophosphate (mg/L as PO_4^{3-})	5.92	3.42	0.15	0.40	0.05	0.13
Total chemical oxygen demand (mg/L)	166	78	132	116	40	40
pH	8.7	8.8	9.1	9.1	9.1	9.5
Color at 455 nm (PtCo unit)	97	<5	109	111	35	20
Filtered UV_{254} (OD)	0.892	0.017	0.900	0.901	0.078	0.053
Calcium hardness (mg/L as $CaCO_3$)	1,375	1,745	665	715	1,280	1,400
Alkalinity (mg/L as $CaCO_3$)	770	350	140	150	70	100
Biomass (g/L)	X	X	1.639	1.772	1.260	1.746

OCWD CCRO & WBMWD ECLWRF ROCs

Cycle No.	First Cycle					
Parameter	Initial WBMWD ROC	Initial OCWD CCRO ROC	WBMWD #1	WBMWD #2	OCWD CCRO #1	OCWD CCRO #2
Silica (mg/L SiO_2)	116	79	130	133	5	8
Nitrate (mg/L as N)	1.4	104.8	1.54	1.58	87.95	90.25
Ammonia (mg/L as N)	310.0	1.3	246.5	235.5	<0.4	<0.4
Orthophosphate (mg/L as PO_4^{3-})	63.5	16.5	25.00	19.50	0.20	0.10
Total chemical oxygen demand (mg/L)	174	204	172	170	194	194
pH	8.3	8.3	8.5	8.5	8.3	8.6
Color at 455 nm (PtCo unit)	325	427	168	173	251	244
Filtered UV_{254} (OD)	0.982	1.365	0.901	0.88	1.332	1.316
Calcium hardness (mg/L as $CaCO_3$)	915	2,150	860	980	900	920
Alkalinity (mg/L as $CaCO_3$)	1,037	1,757	1,077	1,127	677	807
Biomass (g/L)	0.1005	0.1005	0.0890	0.1120	X	X

Cycle No.	Second Cycle					
Parameter	Initial WBMWD ROC	Initial OCWD CCRO ROC	WBMWD #1	WBMWD #2	OCWD CCRO #1	OCWD CCRO #2
Silica (mg/L SiO_2)	X	87	X	X	6.1	11

Nitrate (mg/L as N)	X	104.5	X	X	86.25	87.3
Ammonia (mg/L as N)	X	0.90	X	X	<0.4	<0.4
Orthophosphate (mg/L as PO_4^{3-})	X	16.85	X	X	0.20	0.30
Total chemical oxygen demand (mg/L)	X	204	X	X	206	214
pH	X	7.6	X	X	8.8	8.6
Color at 455 nm (PtCo unit)	X	400	X	X	241	237
Filtered UV_{254} (OD)	X	1.454	X	X	1.558	1.360
Calcium hardness (mg/L as $CaCO_3$)	X	2,210	X	X	960	940
Alkalinity (mg/L as $CaCO_3$)	X	1,797	X	X	650	760
Biomass (g/L)	X	X	X	X	X	X

Cycle No.	Third Cycle					
Parameter	Initial WBMWD ROC	Initial OCWD CCRO ROC	WBMWD #1	WBMWD #2	OCWD CCRO #1	OCWD CCRO #2
Silica (mg/L SiO_2)	X	83	X	X	3	10.5
Nitrate (mg/L as N)	X	101.35	X	X	86.9	89
Ammonia (mg/L as N)	X	0.65	X	X	<0.4	<0.4
Orthophosphate (mg/L as PO_4^{3-})	X	16.20	X	X	0.15	0.20
Total chemical oxygen demand	X	210	X	X	204	208

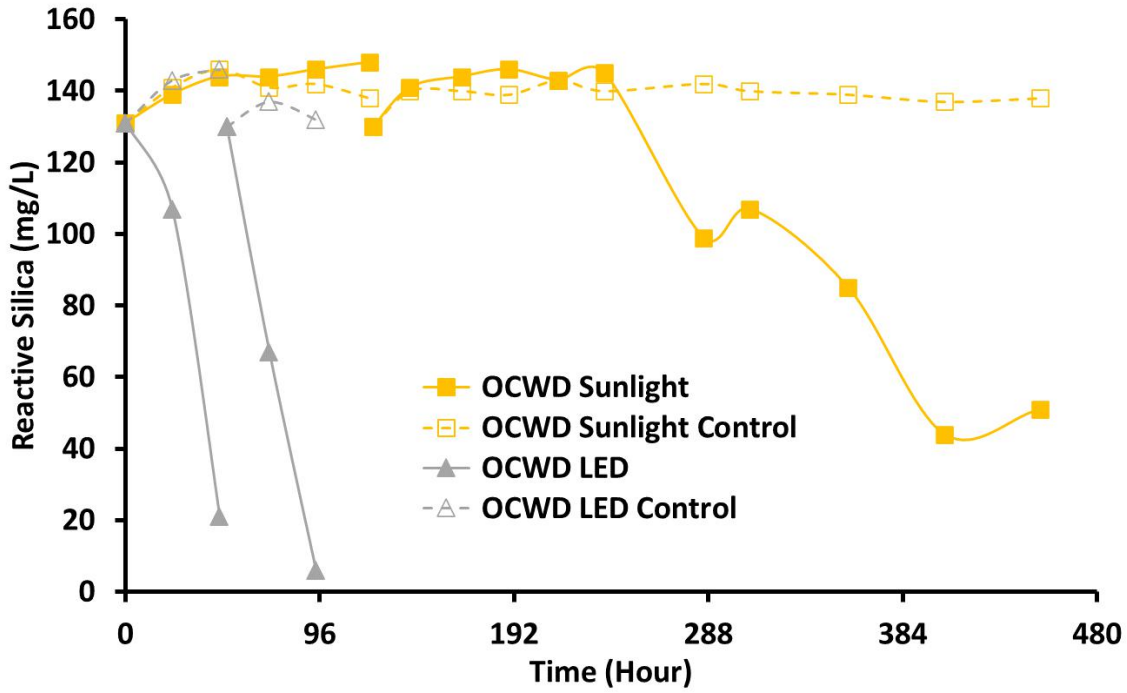
(mg/L)						
pH	X	8.3	X	X	8.8	8.9
Color at 455 nm (PtCo unit)	X	454	X	X	247	250
Filtered UV_{254} (OD)	X	1.426	X	X	1.292	1.420
Calcium hardness (mg/L as $CaCO_3$)	X	2,210	X	X	1,030	990
Alkalinity (mg/L as $CaCO_3$)	X	1,850	X	X	770	900
Biomass (g/L)	X	X	X	X	2.510	2.194

NDMA REMOVAL INVESTIGATION EXPERIMENT

Cycle No.	First Cycle				
Parameters	Initial	OCWD Sunlight #1	OCWD Sunlight Control #1	OCWD LED #1	OCWD LED Control #1
Silica (mg/L SiO_2)	131	148	138	21	146
Nitrate (mg/L as N)	63	64.2	64.1	57.1	63.4
Ammonia (mg/L as N)	9.1	6.6	9.2	<0.4	<0.4
Orthophosphate(mg/L as PO_4^{3-})	8.2	4.75	4.18	0.05	2.15
Total chemical oxygen demand (mg/L)	128	144	136	132	140
Dissolved chemical oxygen demand (mg/L)[b]	130	140	132	132	128
Color at 455 nm (PtCo unit)	202	268	108	165	184
Filtered UV_{254}	0.846	0.773	0.681	0.772	0.763
In vivo Chlorophyll (ug/L)	4.78	4.29	2.15	3.28	3.4
Unfiltered Phycocyanin (ppb)	0	10.99	0	15.66	0.52
Filtered Phycocyanin (ppb)	0	0	0	0	0
Biomass (g/L)	0.185	\	\	\	\

Cycle No.	Second Cycle				
Parameters	Initial	OCWD Sunlight #1	OCWD Sunlight Control #1	OCWD LED #1	OCWD LED Control #1
Silica (mg/L SiO_2)	130	51	138	6	132
Nitrate (mg/L as N)	63.9	64	62.9	54.2	63.1
Ammonia (mg/L as N)	8.6	1.2	7.9	<0.4	<0.4
Orthophosphate(mg/L as PO_4^{3-})	7.6	1.88	2.4	0.03	3.6
Total chemical oxygen demand (mg/L)	136	144	140	128	136

Dissolved chemical oxygen demand (mg/L)[b]	130	140	144	108	124
Color at 455 nm (PtCo unit)	213	272	116	194	198
Filtered UV_{254}	0.853	0.898	0.606	0.787	0.795
In vivo Chlorophyll (ug/L)	5.11	4.86	1.83	4.31	3.27
Unfiltered Phycocyanin (ppb)	3.445	0	0	31.27	5.38
Filtered Phycocyanin (ppb)	0	0	0	0.444	0
Biomass (g/L)	\	13.63	\	13.77	\



Cycle No.	First Cycle		
Parameters	Initial	OCWD Sunlight #1	OCWD Sunlight Control #1
Silica (mg/L SiO_2)	127	23	134
Nitrate (mg/L as N)	54.7	44.5	54.4

Ammonia (mg/L as N)	6.5	<0.4	6.1
Orthophosphate(mg/L as PO_4^{3-})	7.2	0.08	1
Total chemical oxygen demand (mg/L)	144	150	132
Dissolved chemical oxygen demand (mg/L)[b]	140	140	128
Color at 455 nm (PtCo unit)	193	147	104
Filtered UV_{254}	0.906	0.804	0.694
In vivo Chlorophyll (ug/L)	4.54	3.81	2.71
Unfiltered Phycocyanin (ppb)	0	0.8	0
Filtered Phycocyanin (ppb)	0	10.66	0
Biomass (g/L)	0.21	\	\

Cycle No.	Second Cycle		
Parameters	Initial	OCWD Sunlight #1	OCWD Sunlight Control #1
Silica (mg/L SiO_2)	130	35	134
Nitrate (mg/L as N)	53.6	42.4	51.4
Ammonia (mg/L as N)	5.8	<0.4	6.2
Orthophosphate(mg/L as PO_4^{3-})	7.4	0.07	1.2
Total chemical oxygen demand (mg/L)	108	128	144
Dissolved chemical oxygen demand (mg/L)[b]	136	136	128
Color at 455 nm (PtCo unit)	197	156	144
Filtered UV_{254}	0.899	0.807	0.758
In vivo Chlorophyll (ug/L)	4.43	3.57	3.03
Unfiltered Phycocyanin (ppb)	0	0	0
Filtered Phycocyanin (ppb)	4.575	0	0
Biomass (g/L)	\	17.4	\

Experiment A			ng/L	
Date	Sample IDs	Cycle #	NDMA	NMOR
2021-03-03	C1BF #1	1	50.9	121.3
	C1BF #2		49.7	117.6
	C1AF #1		46.6	115.6
	C1AF #2		48.4	113.9
	C1AF #3		47.5	112.9
	C1AF #4		47.1	114.4

2021-03-04	C1DS #1		28.8	42.7
	C1DS #2		27.6	41.3
	C1DSC #1		26.7	33.9
	C1DSC #2		26.8	33.8
	C1DL #1		52.8	112.5
	C1DL #2		51.5	112.5
	C1DLC #1		50.4	113.8
	C1DLC #2		51.4	112.6
2021-03-05	C1DS #1		59.0	37.5
	C1DS #2		101.1	101.8
	C1DSC #1		13.6	7.9
	C1DSC #2		11.4	7.7
	C1DL #1		55.5	108.2
	C1DL #2		54.7	108.1
	C1DLC #1		52.1	110.6
	C1DLC #2		52.0	110.2
	C1ACL #1		56.0	107.8
	C1ACL #2		56.4	108.0
	C1ACLC #1		51.3	112.3
	C1ACLC #2		52.7	112.3
	C2BF #1	2	47.1	109.5
	C2BF #2		47.1	108.9
	C2AF #1		46.6	135.1
	C2AF #2		46.9	109.5
	C2AF #3		46.9	111.5
	C2AF #4		47.2	112.1
2021-03-06	C1DS #1	1	90.9	44.1
	C1DS #2		91.1	44.8
	C1DSC #1		6.7	3.2
	C1DSC #2		7.0	3.6
	C2DL #1	2	48.1	104.7
	C2DL #2		47.8	103.5
	C2DLC #1		45.5	101.6
	C2DLC #2		45.9	102.6
2021-03-07	C1DS #1	1	67.4	19.8
	C1DS #2		70.5	23.0
	C1DSC #1		7.4	7.7
	C1DSC #2		6.9	8.5
	C2DL #1	2	50.1	95.4
	C2DL #2		51.2	95.7
	C2DLC #1		46.2	92.6

	C2DLC #2		46.6	93.9
	C2ACL #1		51.7	96.0
	C2ACL #2		51.4	94.3
	C2ACLC #1		47.4	96.6
	C2ACLC #2		48.4	98.6
2021-03-08	C1DS #1	1	106.2	47.1
	C1DS #2		104.7	48.8
	C1DSC #1		6.0	2.9
	C1DSC #2		5.7	3.2
	C1ACS #1		149.7	83.3
	C1ACS #2		148.7	85.8
	C1ACSC #1		6.4	3.3
	C1ACSC #2		7.1	3.2
	C2BF #1	2	44.0	99.0
	C2BF #2		44.5	97.0
	C2AF #1		44.7	93.3
	C2AF #2		44.0	92.8
	C2AF #3		43.8	94.9
	C2AF #4		44.5	96.7
2021-03-09	C2DS #1		63.9	161.0
	C2DS #2		64.2	158.0
	C2DSC #1		40.6	78.7
	C2DSC #2		38.6	79.0
2021-03-10	C2DS		46.1	68.5
	C2DSC		22.6	29.9
2021-03-11	C2DS		18.4	26.1
	C2DSC		13.4	12.5
2021-03-12	C2DS		16.4	12.5
	C2DSC		8.8	7.0
2021-03-13	C2DS		15.0	14.6
	C2DSC		6.6	5.4
2021-03-15	C2DS		5.8	3.5
	C2DSC		2.7	2.8
2021-03-16	C2DS		5.0	6.8
	C2DSC		1.5	2.2
2021-03-18	C2DS		1.4	nd
	C2DSC		nd	nd
2021-03-20	C2DS		nd	nd
	C2DSC		nd	nd

Experiment B			ng/L	
Date	Sample IDs	Cycle #	NDMA	NMOR
2021-04-07	C1BF #1	1	30.1	79.0
	C1BF #2		30.4	81.0
	C1AF #1		31.8	84.4
	C1AF #2		32.0	83.5
2021-04-08	C1DS #1		28.1	11.9
	C1DS #2		30.6	11.8
	C1DSC #1		14.5	14.4
	C1DSC #2		14.1	14.3
2021-04-09	C1DS #1		23.1	nd
	C1DS #2		23.3	nd
	C1DSC #1		5.1	nd
	C1DSC #2		5.1	nd
2021-04-10	C1DS #1		22.4	nd
	C1DS #2		22.3	nd
	C1DSC #1		2.5	nd
	C1DSC #2		2.6	nd

Experiment C			ng/L	
Date	Sample IDs	Cycle #	NDMA	NMOR
2021-04-15	C1BF #1	1	29.3	79.1
	C1BF #2		32.8	76.0
	C1AF #1		33.5	77.4
	C1AF #2		32.5	78.5
2021-04-16	C1DS #1		30.6	71.8
	C1DS #2		32.8	71.7
	C1DSC #1		29.3	51.2
	C1DSC #2		29.3	52.4
2021-04-17	C1DS #1		27.6	59.2
	C1DS #2		28.0	60.4
	C1DSC #1		23.0	37.9
	C1DSC #2		23.3	37.8
2021-04-18	C1DS #1		21.5	43.8
	C1DS #2		21.0	43.7
	C1DSC #1		14.5	18.0
	C1DSC #2		13.9	16.6
2021-04-19	C1DS #1		16.1	31.6
	C1DS #2		16.7	32.7
	C1DSC #1		8.2	7.6

	C1DSC #2		8.0	7.2
2021-04-20	C1DS #1		13.8	29.7
	C1DS #2		13.7	30.0
	C1DSC #1		6.0	nd
	C1DSC #2		7.1	nd
2021-04-21	C1DS #1		11.0	23.6
	C1DS #2		11.7	23.5
	C1DSC #1		3.8	nd
	C1DSC #2		4.1	nd
2021-04-22	C1DS #1		9.3	18.3
	C1DS #2		9.4	18.3
	C1DSC #1		2.9	nd
	C1DSC #2		2.8	nd
2021-04-23	C1DS #1		11.1	26.5
	C1DS #2		12.4	27.0
	C1DSC #1		3.1	4.7
	C1DSC #2		3.1	4.3
2021-04-24	C1DS #1		9.5	19.6
	C1DS #2		9.7	19.9
	C1DSC #1		2.6	4.4
	C1DSC #2		2.7	4.5
	C2BF #1	2	34.6	79.3
	C2BF #2		34.5	79.3
	C2AF #1		34.6	79.0
	C2AF #2		34.6	78.4
2021-04-25	C2DS #1		24.9	62.0
	C2DS #2		23.0	63.5
	C2DSC #1		20.6	54.7
	C2DSC #2		23.5	56.1
2021-04-26	C2DS #1		17.6	42.6
	C2DS #2		17.2	51.3
	C2DSC #1		11.1	26.7
	C2DSC #2		11.2	24.3
2021-04-27	C2DS #1		15.9	58.2
	C2DS #2		15.8	57.2
	C2DSC #1		6.7	18.9
	C2DSC #2		11.6	16.7
2021-04-28	C2DS #1		13.5	52.4
	C2DS #2		14.3	54.5
	C2DSC #1		3.4	12.1
	C2DSC #2		3.8	9.3

2021-04-29	C2DS #1		11.9	41.7
	C2DS #2		11.6	43.9
	C2DSC #1		1.7	10.6
	C2DSC #2		1.6	7.8
	C3BF #1	3	30.2	80.3
	C3BF #2		31.5	84.0
	C3AF #1		31.8	82.3
	C3AF #2		32.3	84.4
2021-04-30	C3DS #1		31.4	131.3
	C3DS #2		30.2	137.3
	C3DSC #1		26.4	73.1
	C3DSC #2		27.0	72.3
2021-05-01	C3DS #1		33.4	167.4
	C3DS #2		33.2	166.3
	C3DSC #1		21.3	53.9
	C3DSC #2		21.2	54.7
2021-05-02	C3DS #1		29.8	155.9
	C3DS #2		29.7	155.1
	C3DSC #1		13.4	35.8
	C3DSC #2		13.2	35.1
2021-05-03	C3DS #1		27.2	100.2
	C3DS #2		27.1	109.1
	C3DSC #1		12.4	21.0
	C3DSC #2		13.7	20.4
2021-05-04	C3DS #1		22.7	83.1
	C3DS #2		22.4	83.2
	C3DSC #1		8.2	13.4
	C3DSC #2		7.5	11.6
2021-05-05	C3DS #1		17.7	51.6
	C3DS #2		17.1	52.6
	C3DSC #1		5.2	10.1
	C3DSC #2		5.5	8.2
2021-05-06	C3ACS #1		14.2	29.0
	C3ACS #2		14.4	26.8
	C3ACSC #1		2.2	7.6
	C3ACSC #2		2.4	6.0

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