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FINAL PROJECT REPORT

Improving Energy Efficiency and Performance of Wastewater Recycling

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Improving Energy Efficiency and Performance of Wastewater Recycling is the final report for the *Improving Energy Efficiency and Performance of Wastewater Recycling* project (EPC-18-008) conducted by MicroBio Engineering Inc. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

This project advanced the science and engineering of the raceway pond process, an algae-based wastewater treatment technology that has lower electricity usage than conventional activated sludge processes and better treatment performance than conventional treatment ponds. The principle underlying raceway ponds is the ability of green microalgae to use sunlight through photosynthesis to facilitate wastewater treatment. Instead of relying on energy-intensive mechanical aeration to oxygenate the wastewater, microalgae use photosynthesis to provide a part of the oxygen needed for treatment of bacteria in wastewater to break down the organic matter and transform ammonium. While raceway ponds are already proven to accomplish secondary treatment at full scale, advancements developed and tested during this project increased their nitrogen removal capability.

These advancements were developed and tested at laboratory, pilot, and full scale. Process improvements developed at pilot scale were implemented at a community facility in California's Central Valley, including equipment additions and process modifications to maintain sufficient dissolved oxygen, increased algal and bacterial concentrations, and including a filtration stage of treatment. The resulting effluent quality produced by raceway ponds is intended to meet an annual average discharge limit of less than 10 milligrams per liter of total nitrogen and the requirements for disinfected tertiary recycled water, as defined in Title 22 of the California Code of Regulations.

Keywords: wastewater treatment ponds, algae, nitrification

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Executive Summary

Background

The State of California has ambitious climate and energy goals, including energy conservation. One promising avenue to reduce statewide energy consumption is to address electricity use at the municipal level, with emphasis on the co-benefit of cost reduction. For many communities, water conveyance and treatment systems are the biggest consumers of municipal electricity. In California, water systems in general use approximately 20 percent (about 175,950 gigawatt-hours [GWh] per year) of the state's electricity, with about 2 percent (approximately 3,500 GWh per year) of that energy being devoted to wastewater treatment (Esrciva-Bou et al. 2022). Electricity demand for municipal wastewater treatment is expected to increase substantially due to increased population, greater demand for wastewater recovery and reuse, and new regulations now requiring nitrogen removal and eventually perhaps phosphorus removal as well.

Advancements in wastewater treatment technologies to reduce electricity intensity and enhance peak shifting would also improve greenhouse gas emissions and the resilience of wastewater treatment plants.

Project Purpose and Approach

This project advanced an existing nature-based wastewater treatment technology known as algal raceway ponds. Raceways are a solution to the growing issues of treatment affordability for rural communities, by using less expensive infrastructure than conventional activated sludge facilities while achieving high efficiency in electricity use. The overarching goals of this project were to develop year-round total nitrogen removal capabilities for raceway ponds and to test membrane ultrafiltration of treatment pond effluent, as an alternative to conventional granular media filtration, for tertiary-level water recycling applications.

Raceway ponds are shallow (30 to 100-centimeter), mixed channels that achieve higher algae productivity than standard stabilization and facultative pond systems, which are deep and mostly unmixed. This increased algae productivity provides more photosynthetic dissolved oxygen and nutrient assimilation in algal cells. The mixing provides a more uniform environment for the microbes performing treatment, increases their contact with the water, and makes effluent quality more uniform versus conventional treatment ponds. While the mixing does consume additional power, it helps otherwise low-power intensity pond systems to meet new nitrogen discharge limits and facilitates algae removal prior to filtration.

MicroBio Engineering Inc. proposed to use targeted aeration in the raceway ponds to supplement the solar photosynthetic oxygenation provided by algae, specifically during winter and mainly at night. Targeted aeration provides an additional benefit, which is the potential for peak power demand management. By storing wastewater in ponds during the day, pond systems can perform the power-demanding mechanical aeration during off-peak hours.

Key Results and Conclusions

Pilot- and full-scale studies were performed. The key findings from the 1000-L pilot-scale raceway studies were that:

- Raceways achieved the most reliable reduction of total ammonia nitrogen, to less than or equal to (≤) 5 milligrams per liter (mg/L), with an eight-day hydraulic residence time and a volatile suspended solids concentration of 400-800 mg/L.

The key findings from full-scale studies were as follows.

- Return of settled algae slurry into the raceway pond decreased ammonia nitrogen in the winter of 2022/2023 compared to the previous winter.
- Operational optimizations resulted in the facility achieving 86-percent total ammonia nitrogen removal in the winter of 2022/2023, a 10- to 25-percent increase over previous years, prior to optimization.
- During the final study year, the integration of all optimization strategies resulted in 9 of 12 months meeting the total nitrogen < 10 mg/L monthly permitted threshold and the achievement of annually averaged total nitrogen < 10 mg/L (assuming implementation of denitrification at 90-percent removal of oxidized nitrogen).
- Optimization decreased the amount of aeration needed by 15 percent, comparing the first and last years of the project.
- By minimizing aeration, the electricity consumption of the raceway system was projected to be up to 66 percent lower than the activated sludge process.

The key findings from the membrane filtration studies were that:

- Tubular membrane ultrafiltration, while able to consistently produce a high-quality effluent regardless of feed quality, was not an economically viable option for polishing secondary-level effluent from a heavily loaded conventional pond system.

Knowledge Transfer and Next Steps

The advancement gained over the course of this project in the energy efficiency of raceway ponds for treating municipal water has been and will continue to be disseminated in a variety of ways. Most immediately, these results have been disseminated through periodic meetings with raceway facility operators and water district managers. The optimization strategies developed over the course of this project provide these communities with operational alternatives to attain improved water quality, without replacing their facilities with costly, energy-intensive activated sludge facilities.

In an effort toward wider dissemination and eventual adoption, MicroBio Engineering Inc. reached out to multiple communities and county agencies that could benefit from improving treatment performance while maintaining low energy costs. To date, MicroBio Engineering Inc. has briefly contacted 19 municipalities within a 300-mile radius of San Luis Obispo that operate conventional pond systems for wastewater treatment. Four of those were receptive to having

MicroBio Engineering Inc. visit their facility to discuss their needs and learn about the potential of raceway pond technology.

Moving forward, MicroBio Engineering Inc. will continue to reach out to California facilities that may have difficulty meeting new, lower-nitrogen discharge requirements. As the most likely adopters are identified, MicroBio Engineering Inc. will work with them to procure funding from organizations such as the California Energy Commission, the United States Department of Energy, and the United States Department of Agriculture for demonstration-phase projects. Upon successful completion of the demonstration-scale projects, efforts will be focused on working with communities to secure grants and low interest loans from the United States Department of Agriculture's rural community development funds for the implementation of raceway ponds.

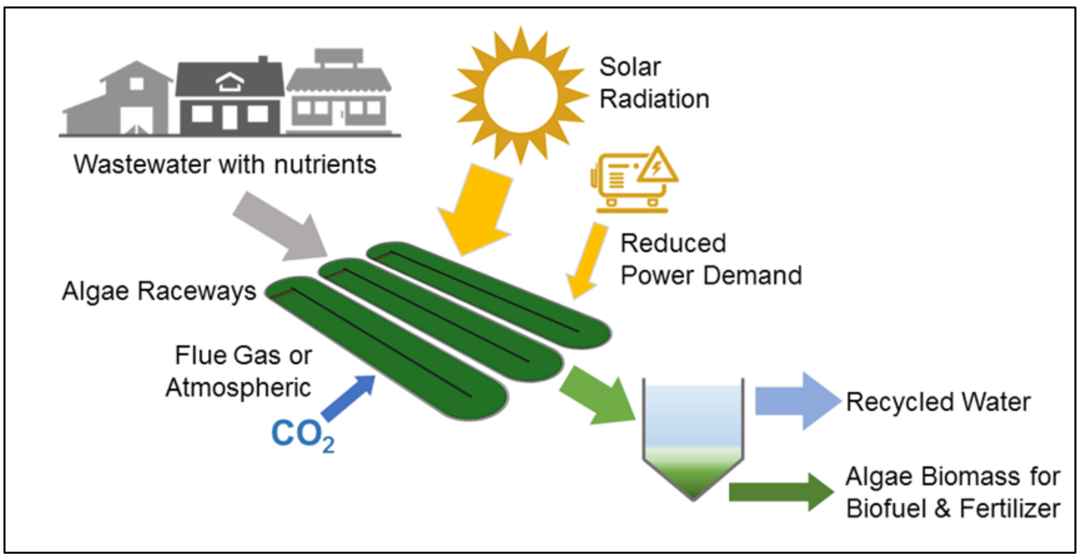
Other important next steps will contribute toward a broader effort of dissemination to the wastewater industry as a whole. These involve presenting the results from this project as a case study at conferences and meetings organized by the California Rural Water Association, the California Water Environment Association, and, eventually, the National Rural Water Association.

CHAPTER 1: Introduction

Project Origin and Goals

MicroBio Engineering Inc. (MBE) has worked to improve the algae raceway pond technology for wastewater treatment and algae production for many years. The process uses microalgae and bacteria for photosynthesis-based wastewater treatment (Figure 1) that can be implemented as either an upgrade to existing treatment systems or as a greenfield installation. The algal-bacterial cultures grown in paddlewheel-mixed raceway ponds use the organic carbon and other nutrients in the wastewater to support their growth and, in the process, treat the wastewater. The algal and bacterial cells are then separated from the effluent of the treatment process by gravity settling, with the resulting effluent treated by membrane filtration and disinfection, to achieve unrestricted water reuse standards (State Water Resources Control Board 2018).

Figure 1: Raceway Pond Process Overview



Source: MicroBio Engineering Inc.

Raceway ponds use two processes to accomplish nitrogen removal: (1) assimilation into algal and bacterial biomass, and (2) bacterial nitrification/denitrification. A key strategy in the present project was intermittent aeration of a full-scale raceway pond to nitrify influent ammonium nitrogen (measured as total ammonia nitrogen, TAN) to nitrate nitrogen (NH_4^+ [ammonium ion] to NO_3^- [nitrate ion]), particularly in winter when algae are less productive. This process is best performed at dissolved oxygen (DO) concentrations of 2 to 4 milligrams per liter (mg/L). The nitrification step is followed by denitrification of nitrate to nitrogen gas (NO_3 to N_2), which bubbles out of the water, completing nitrogen removal. (Denitrification is a well-established wastewater treatment process and thus was not emphasized in the present research.) The successful implementation of nitrogen removal at a full-scale facility allows a dataset to be built over time to support technology decisions by other wastewater treatment plant (WWTP) owners that need to protect local water sources from nitrogen contamination and reduce their energy demand.

The overall project goals were to:

- Develop a low-energy-intensity wastewater treatment process to reduce the electrical demand from wastewater treatment facilities in California.
- Develop a low-cost alternative wastewater treatment technology to enable disadvantaged communities to upgrade their existing facilities to meet discharge requirements.
- Ensure that the wastewater treatment technology is robust for all seasons, reliable, and able to meet discharge limits year-round.

Description of the Municipal Wastewater Treatment Industry in the US, California, and Small and Disadvantaged Communities

In disadvantaged communities, the burden of wastewater treatment is a major and growing financial problem of which power demand is a major part. Accustomed to the low capital and operating expenses of basic lagoon/pond treatment systems, which are by far the most predominant centralized treatment system employed in these small rural communities (Goad 2011), and limited by a small, often low-income ratepayer base, such communities find it financially unfeasible to upgrade to conventional mechanically aerated activated sludge technologies without external grants.

Wastewater Treatment Energy Use and Management Methods

Electricity demand for municipal wastewater treatment is expected to increase substantially due to increased population, greater demand for wastewater recovery and reuse, and new regulations now requiring nitrogen removal and eventually phosphorus removal as well. For many communities, their wastewater treatment plant is the biggest single consumer of electricity — sometimes accounting for as much as 30 percent of a municipality's total electricity demand. Nationwide, this adds up to almost $2 billion in annual electricity costs (U.S. Department of Energy n.d.).

In terms of flow treatment, the most prevalent biological methods for treating municipal wastewater are conventional activated sludge processes, which involve increasing the concentration of heterotrophic and nitrifying bacteria in the wastewater, along with intense aeration to supply the substantial amount of oxygen needed to drive the bacterial treatment. The intensity and duration of aeration required by this technology are a large part of the reason that wastewater treatment facilities consume so much of a municipality's annual energy.

Pond-based Treatment, Performance Improvement Needs, and Energy Management Opportunities

A promising alternative to the energy-intensive activated sludge process is to combine the capabilities of bacteria to oxidize wastes with the capabilities of microalgae to produce oxygen. In addition, both algae and bacteria assimilate nitrogen and phosphorus, which can be leveraged for nutrient removal. These types of microalgal-bacterial processes for wastewater treatment are already in use all over the country in the form of conventional pond systems. Conventional pond systems (sometimes called waste stabilization ponds) are engineered water bodies in which sewage, stormwater, and greywater may be treated. However, these systems require long hydraulic residence times (HRT) to achieve sufficient treatment. They also tend to struggle with reliability in the colder months, due to cooling of wastewater and the resulting slowed biological activity.

Research Needs

Despite its advantages, a major limitation of the raceway pond process, particularly in temperate climates, is insufficient nitrogen removal during winter months.

The reasons for this include:

1. Short winter day length, leading to low algal productivity, oxygen production, and nutrient assimilation. Oxygen is required for oxidation of both organic matter and ammonium nitrogen (nitrification).
2. Colder temperatures in the winter slow all microbial growth, including that of algae, heterotrophic bacteria, and nitrifying bacteria, resulting in slower rates of nitrification and therefore the need for additional nitrifier biomass to offset reduced nitrification rates.

As facility permits come up for renewal, the California Regional Water Quality Control Boards are almost always including in permit renewals a total nitrogen (TN) limit of <10 mg/L on at least an annual average basis, with some regions requiring monthly averaged TN of <10 mg/L. This shift in permit requirements necessitates optimization of algal raceways to be a competitive technology and a viable upgrade alternative to the complete replacement of traditional pond systems with more energy-intensive conventional activated sludge systems.

CHAPTER 2: Project Approach

Project Team and Resources

The project team consisted of:

- Staff from the prime contractor, MBE, San Luis Obispo.
- Research staff at California Polytechnic State University, San Luis Obispo (Cal Poly SLO).
- Undergraduate and graduate students at Cal Poly SLO.
- Delhi County Water District Wastewater Treatment Plant staff and management.
- San Luis Obispo Water Resource Recovery Facility (SLO WRRF) operators and staff from the City of San Luis Obispo.
- Templeton Community Services District wastewater treatment staff.

MBE is a California engineering firm that is focused mainly on technology research and development, and consulting. The company is made up of 15 employees who come from a diverse range of educational, technical, and cultural backgrounds. The company uses this wide range of expertise to help solve problems within the industries of microalgae cultivation, wastewater treatment, and biofuels production.

Cal Poly SLO is a public university in the California State University system. The university is well known for its wealth of research opportunities and focus on hands-on learning opportunities for students. This project involved the Sustainable Utilities Research and Education (SURE!) program that is part of Cal Poly's Civil and Environmental Engineering department. The SURE! program has been engaging students in hands-on water and energy related research since 2007. The program also manages a research field station located at the SLO WRRF. The research facility houses various pilot-scale systems for research use that allow students to work hands-on with the local utility to study more affordable and sustainable technologies.

In addition to the partnership with the City of San Luis Obispo, the project could not have been completed without the partnership of the Delhi County Water District (Delhi CWD). The Delhi CWD is in Merced County, which is a part of the Central Valley region of California. The utility serves the 13,000 residents of Delhi, as well as commercial entities. The Delhi CWD WWTP, which is owned and operated by the Delhi CWD, occupies a 48-acre property in Delhi and provides wastewater services to the community. Prior and recent partnerships with the Delhi CWD have provided invaluable opportunities to improve wastewater treatment for small and rural communities like Delhi.

Study Sites

San Luis Obispo, CA

The SURE! Field Station is a 1-acre research facility located within the property of the San Luis Obispo WRRF (Figure 2, left). The research site features various types of pilot-scale systems for algae cultivation, wastewater treatment, and solids separation as well as on-site basic water quality testing facilities (Figure 2, right). This project utilized ten pilot-scale (1,000-liter [L], 3.4-square-meter [m^2]) raceway ponds and other equipment and infrastructure to control the experimental conditions of the systems.

Figure 2: Location and Operation of the SURE! Field Station at San Luis Obispo Water Resource Recovery Facility

Sources: [Left] Image adapted from Google Earth by MicroBio Engineering Inc.
Source: [Right] MicroBio Engineering Inc.

The raceway ponds were operated in duplicate, where each set of two ponds had only one variable at a time that was different from the other sets. Each raceway was equipped with automated data monitoring and recording equipment. Datapoints were collected and stored at 1-hour intervals from probes measuring dissolved oxygen (DO), the potential of hydrogen (pH), and temperature. All data recorded from the probes was stored in a cloud-based system for basic data visualization.

The cloud-based system also ensured that the air could be dosed automatically in response to real-time DO concentration, just like a full-scale facility. It also enabled energy consumption data to be recorded.

Delhi, CA

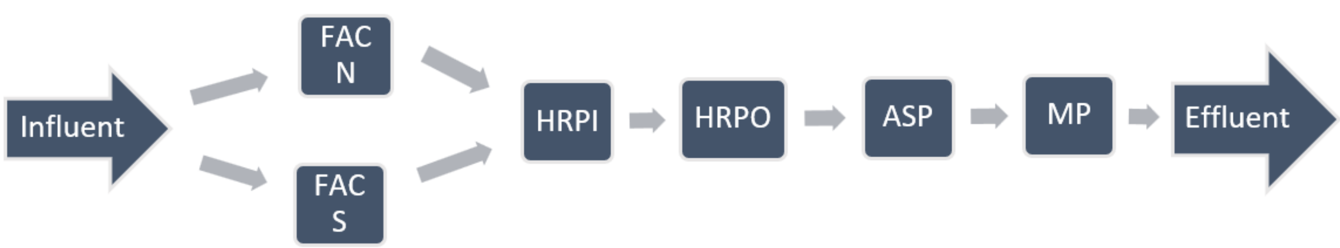
The Delhi CWD WWTP is a modified pond system that is located within the community of Delhi and is designed to treat up to 1.2 million gallons per day (MGD). The treatment plant uses a system of six ponds to reach its effluent quality standards (Figure 3). Labels denote abbreviated pond names.

Figure 3: Aerial View of Delhi County Wastewater Treatment Plant

Source: Image adapted from Google Earth by MicroBio Engineering Inc.

A slightly simplified process flow diagram for the Delhi CWD WWTP is shown in Figure 4 below. The influent water is first screened to remove large solids and debris. Next, the flow is split and sent to both facultative north (FAC N) and facultative south (FAC S) ponds. From there, the flows enter the inner raceway, called a high-rate pond (HRPI). HRPI leads to the outer high-rate pond (HRPO), and the wastewater continues to one of the two algae settling ponds (ASP). After settling, the water flows into the maturation pond (MP) and into percolation beds, from where it eventually returns to the ground water.

Figure 4: Simple Process Flow at Delhi CWD Wastewater Treatment Plant



Source: Feldsien, 2024.

Templeton, CA

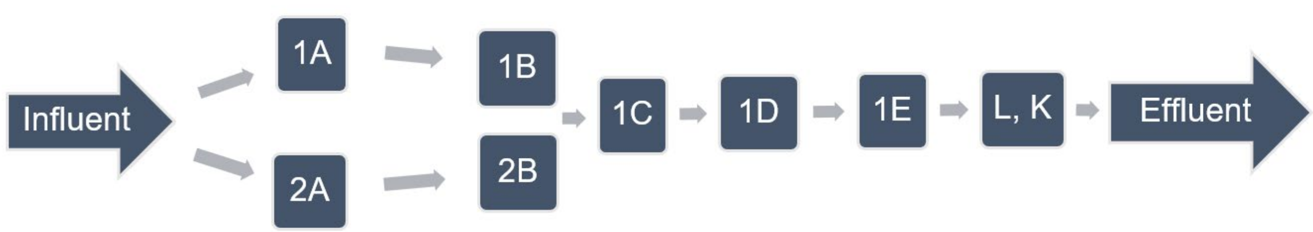
The final site involved in the project was the Meadowbrook WWTP, where the membrane filter was tested. The Meadowbrook WWTP is a conventional pond system that is located within the City of Templeton and is designed to treat up to 0.5 MGD. The treatment plant system consists of four aerated facultative ponds, three polishing ponds, sand filters, and percolation ponds to reach its effluent quality standards. An aerial view of the plant is shown in Figure 5, with labels denoting the abbreviated pond names.

Figure 5: Aerial View of Meadowbrook Wastewater Treatment Plant

Source: Image adapted from Google Earth by MicroBio Engineering Inc.

A process flow for the Meadowbrook WWTP is shown in Figure 6. The influent flow first goes through a screen and then is split between the first set of facultative ponds, 1A and 2A. From there, the flow from 1A goes to 1B and the flow from 2A goes to 2B. Ponds 1B and 2B are also facultative ponds. Next, the flows from ponds 1B and 2B are combined and sent to a series of polishing ponds (1C, 1D, 1E). Before 2019, the effluent from 1E would flow downhill to pressurized sand filters on the east end, before being sent to percolation basins across the freeway. After May 2019, Ponds L and K were brought online to help with treatment deficiencies before feeding the sand filters.

Figure 6: Simple Process Flow at Meadowbrook WWTP



Source: MicroBio Engineering Inc.

Project Objectives

MBE designed experiments and collected data at laboratory, pilot, and full scale in an effort to achieve the following major objectives:

- Measure year-round wastewater treatment performance of an algae-based wastewater treatment system through three distinct systems.
- Measure year-round electrical consumption from an algae-based wastewater treatment system.
- Determine the rate and timing of supplemental mechanical aeration required for small- and large-scale nitrification to meet nutrient discharge limits during low-performing winter months.
- Pilot and measure fouling rates of innovative low-energy membrane filtration systems, which filter the effluent of the algal wastewater treatment process to meet Title 22 water reuse regulations.

Contractual Task Descriptions

The following descriptions are for the specific technical tasks that MBE committed to completing.

TASK 2: Test Set 1.1 — Central Valley Configuration and Setup

The goal of this task was to upgrade and add to the infrastructure at the Central Valley facility to achieve lower-nitrogen discharges and improve electrical efficiency of nitrogen removal. The upgrades were mainly to improve mixing and aeration equipment. The upgrades were also intended to ensure mechanically reliable operation over the course of the project.

TASK 3: Test Set 1.2 — Operational Optimization Experiments

The goals of this task were to collect weekly data to determine the baseline annual aeration requirements at the Central Valley facility for both bacterial treatment and electricity demand purposes. Determining the baseline requirements would also help to calculate the corresponding appropriate algae concentrations to perform nitrogen removal.

TASK 4: Test Set 1.3 — Biological Treatment Performance Data Collection in the Central Valley

The goals of this task related to the Central Valley facility were to compile and analyze sufficiently large data sets to maximize the use of photosynthetic oxygen over mechanical aeration by making weekly adjustments to optimize the aeration schedule and the suspended solids concentration. The secondary goal was to demonstrate demand scheduling capability and characterize bioflocculation performance.

TASK 5: Test Set 1.4 — Central Valley Recycled Water Filtration Studies

The goals of this task were to evaluate the use of membrane filtration technology at the Central Valley facility to determine power use, total costs, and various other requirements to produce water of suitable disinfection and unrestricted reuse per California's Title 22 water recycling regulations.

TASK 6: Test Set 2.1 — Pilot System Configuration of Selected Effluent Treatment

One goal of this task was to determine which effluent available at the San Luis Obispo WRRF was the most relevant and had the best market demand. The choice was between primary clarifier effluent (PE)[1] and reclaimed wastewater (RWW).[2] The second goal was to re-configure the pilot facility valve settings to receive that selected effluent if necessary.

TASK 7: Test Set 2.2 — Operational Optimization Experiments of Selected Effluent

The goals of this task were to determine the optimal aeration schedule at the pilot facility for both treatment and demand schedule purposes and the corresponding appropriate algae concentrations to perform nutrient removal for the selected influent source (primary clarifier effluent).

TASK 8: Test Set 2.3 — Biological Treatment Performance Data Collection of Selected Effluent

The goals of this task related to the pilot facility were to compile and analyze sufficiently large data sets to maximize the use of photosynthetic oxygen over mechanical aeration by making weekly adjustments to optimize the aeration schedule and the suspended solids concentration. The secondary goal was to demonstrate demand scheduling capability and characterize bioflocculation performance. The experimental pilot facility was to be designed to remove nutrients, with a focus on carbon and nitrogen, from primary effluent to the standards met by previous successful scenarios.

TASK 9: Test Set 2.4 — Recycled Water Filtration Studies of Selected Effluent

The goals of this task were to evaluate filtration technology at the pilot facility to determine power use, total costs, and various other requirements to produce water of suitable disinfection and unrestricted reuse per California's Title 22 water recycling regulations.

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[1] Primary-clarified effluent: Wastewater treated for removal of large debris, grit, and most settleable solids, as defined for the pilot raceway site by MicroBio Engineering Inc.

[2] Reclaimed wastewater: Wastewater treated for removal of most organic matter, then nitrified, filtered, and disinfected, as defined for the pilot raceway site by MicroBio Engineering Inc.

CHAPTER 3: Results

Over the course of three years, the project team was able to accomplish all four of the overall project objectives outlined in CHAPTER 2: Project Approach. The outcomes of the objectives were:

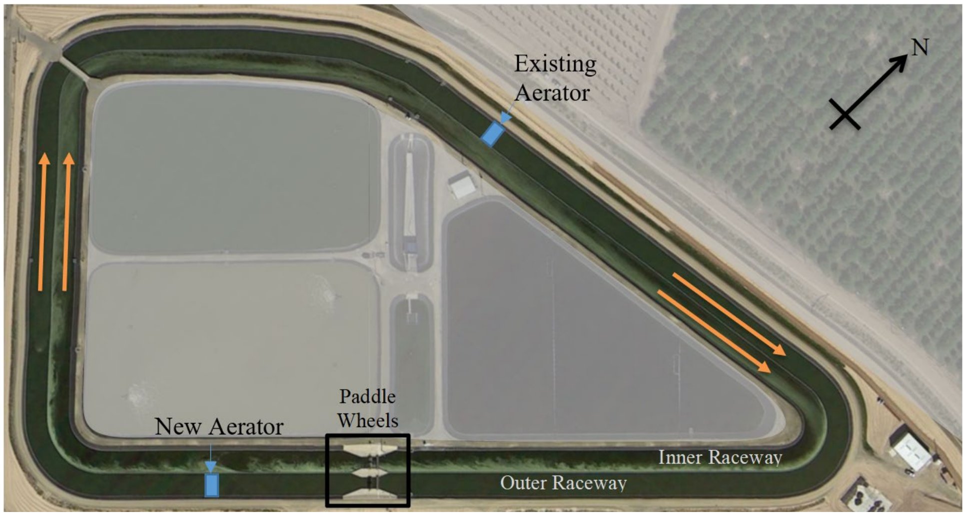
- Year-round measurements of wastewater treatment performance for a pilot-scale, algae-based wastewater treatment system (see TASK 8: Test Set 2.3 — Biological Treatment Performance Data Collection of Selected Effluent Treatment at Pilot Scale).
- Year-round measurements of wastewater treatment performance for a full-scale, algae-based wastewater treatment system (see TASK 3: Test Set 1.2 — Operational Optimization Experiments).
- Year-round measurements of wastewater treatment performance for a full-scale, algae-based wastewater treatment system with solids recycling (see TASK 4: Test Set 1.3 — Biological Treatment Performance Data Collection in the Central Valley).
- Year-round calculated electrical consumption from an algae-based wastewater treatment system (see TASK 10: Project Benefits).
- Optimization of the rate and timing of supplemental mechanical aeration required for pilot scale (see TASK 7: Test Set 2.2 — Operational Optimization Experiments of Selected Effluent Treatment at Pilot Scale) and large-scale nitrification (see TASK 3: Test Set 1.2 — Operational Optimization Experiments) to meet nutrient discharge limits during low-performance winter months.
- Piloting and measurement of fouling rates of an innovative low-energy membrane filtration system (see TASK 5: Test Set 1.4 — High Flux — Recycled Water Filtration Studies and TASK 9: Test Set 2.4 — High Recovery — Recycled Water Filtration Studies).

TASK 2: Test Set 1.1 — Central Valley Configuration and Setup

During the summer and early fall of 2020, several infrastructure changes were made to the Delhi County Water District WWTP. These site modifications were in furtherance of experimental operations at full scale to achieve energy efficient, low-cost, year-round nitrogen removal.

The first change made at the facility was the purchase and installation of a second aerator for the outer raceway pond (a.k.a. the HRPO). Figure 7 indicates the locations of both the previously existing and the new aerator in the outer raceway. The new aerator, like the existing aerator, is a steel-fin floating brush aerator.

Figure 7: Aerial View of the Delhi WWTP With 2020 Infrastructure Upgrades

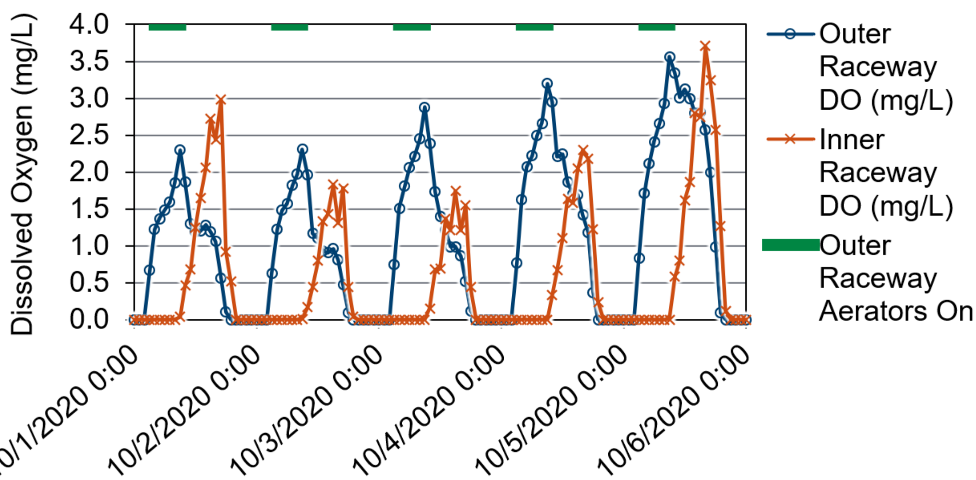


Orange arrows show the direction of water circulation. White text indicates the inner and outer raceways. The black box shows where the paddle wheels are located, including the new motor. Blue boxes indicate locations of existing and new aerators in the outer raceway.

Source: Image adapted from Google Earth by MicroBio Engineering Inc.

Following the addition of the second aerator, improvements in nitrification and aeration efficiency were monitored by regularly sampling both the non-aerated inner raceway and the aerated outer raceway. Within the first three months following installation, the outer raceway removed twice as much total ammonia nitrogen as the inner raceway, providing the first indication that the inclusion of the second aerator facilitated more nitrification. Additionally, Figure 8 illustrates the longer period of positive DO concentration in the aerated outer raceway compared to the inner raceway immediately following the addition of the second aerator.

Figure 8: Hourly DO Concentration of Raceway Ponds in Delhi, CA



Time series data of dissolved oxygen measured hourly by probes installed in the raceway ponds at the Delhi CWD WWTP. The data shown were collected immediately following the addition of a second aerator in the outer raceway pond. The green lines indicate the hours that the aerators in the outer raceway were turned on each day.

Source: MicroBio Engineering Inc.

The second infrastructure change made at the full-scale facility in Delhi was the replacement of the motor controlling the outer raceway paddlewheel. This upgrade was intended to increase the channel velocity within the outer raceway, allowing for better mixing and better suspension of the biological treatment organisms (a combination of microalgae and bacteria). The new motor increased the rotational speed of the paddlewheel by 96 percent, which corresponded to a 60-percent increase in channel velocity in the outer raceway. The upgraded motor also included a variable frequency drive that could facilitate energy savings by adding the ability to reduce paddlewheel speed during peak energy demand hours. However, to limit the experimental variables, the paddlewheel speed was held constant during this project.

TASK 3: Test Set 1.2 — Operational Optimization Experiments

To achieve better conditions for raceway pond nitrogen removal, experimental configurations and operational optimizations were tested in the full-scale HRPO at Delhi County Water District WWTP from July 2020 through June 2021. These experiments included operational changes to the aeration schedule for the brush aerators in the HRPO.

The optimization of the aeration schedule was based on the concentration of TAN in the HRPO effluent. When the TAN concentrations measured steadily less than 2 to 5 mg/L, a reduction in the duration of aeration was considered and usually implemented. Likewise, if the TAN concentration in the HRPO increased and/or the DO was low, a change in the aeration schedule was considered. Table 1 describes each change made over the optimization period.

Table 1: Summary of Aeration Demand Scheduling Changes in the HRPO

Dates	Hours of Aeration	Duration (Hours)
7/27/2020 – 10/20/2020	2:00 AM – 9:00 AM	7
10/20/2020 – 3/16/2021	6:00 PM – 8:00 AM	14
3/16/2021 – 4/27/2021	10:00 PM – 8:00 AM	10
4/27/2021 – 5/18/2021	12:00 AM – 6:00 AM	6
5/18/2021 – 6/8/2021	8:00 PM – 2:00 AM	6
6/8/2021 – 6/15/2021	9:00 PM – 2:00 AM	5
6/15/2021 – 6/30/2021	9:00 PM – 9:00 AM	12

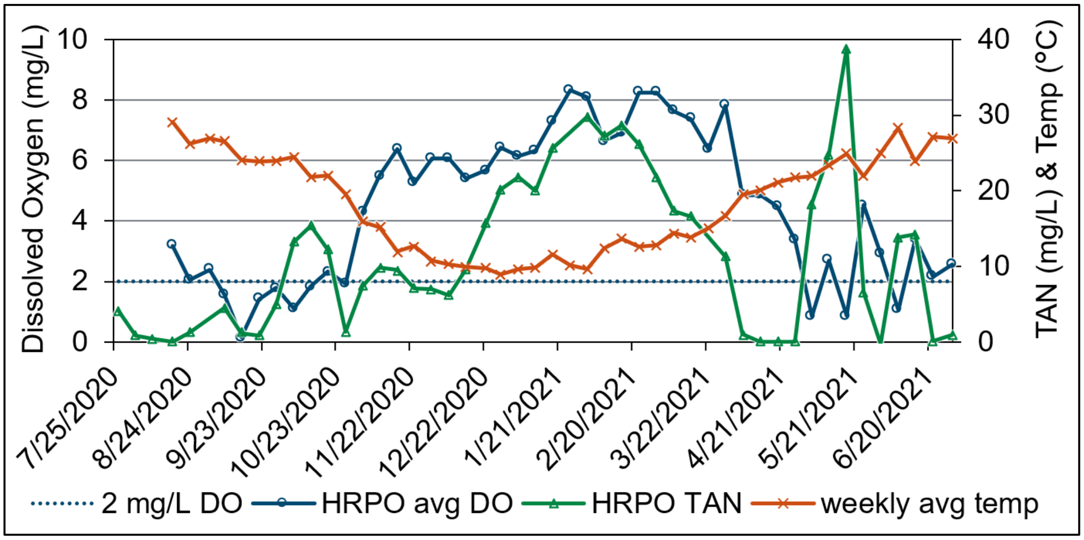
Aeration demand scheduling optimization was completed using two brush aerators located in the outer raceway pond from July 2020 to June 2021 at the full-scale treatment facility in Delhi, CA.

Source: MicroBio Engineering Inc.

The aeration modifications appeared to improve treatment performance most noticeably in the fall and early winter. In the fall of 2020, the TAN increased for three weeks in a row, starting on September 29 (Figure 9). Leading up to that date, the weekly average DO concentration dropped below 2 mg/L — low enough to likely limit nitrification. In response, the hours of aeration were doubled from 7 to 14 hours per day. Within 7 days, the TAN began to drop and within 14 days the TAN was reduced to a near non-detectable level (Figure 9). With this increase in aeration duration, the TAN concentration was maintained at or below 10 mg/L for

8 weeks, whereas, in previous years, the TAN tended to exceed 10 mg/L during this period of the year.

Figure 9: Weekly Average DO, Total Ammonia Nitrogen, and Water Temperature in the HRPO



Time series data of weekly average DO, TAN, and water temperature in the HRPO at the Delhi WWTP from July 2020 to June 2021. The dashed blue line indicates 2 mg/L DO, which is the minimum concentration for reasonable nitrification rates. The May 2021 TAN spike was likely due to increased TAN in the facultative pond effluent (32 mg/L to 42 mg/L from April to May, followed by 25 mg/L in June).

Source: MicroBio Engineering Inc.

However, the late winter season of 2020-2021 showed that, even when sufficient DO was provided, additional factors were needed to promote complete nitrification and/or algal nitrogen assimilation of the TAN. This was particularly apparent toward the end of December, when the DO still averaged 6 mg/L on a consistent week-to-week basis but TAN concentrations kept increasing, until reaching a peak of approximately (~) 30 mg/L in February 2021. The time frame that corresponded to the highest TAN concentrations also corresponded to some of the coldest water temperatures, suggesting that the decreased temperature was likely a major contributing factor to the incomplete TAN removal.

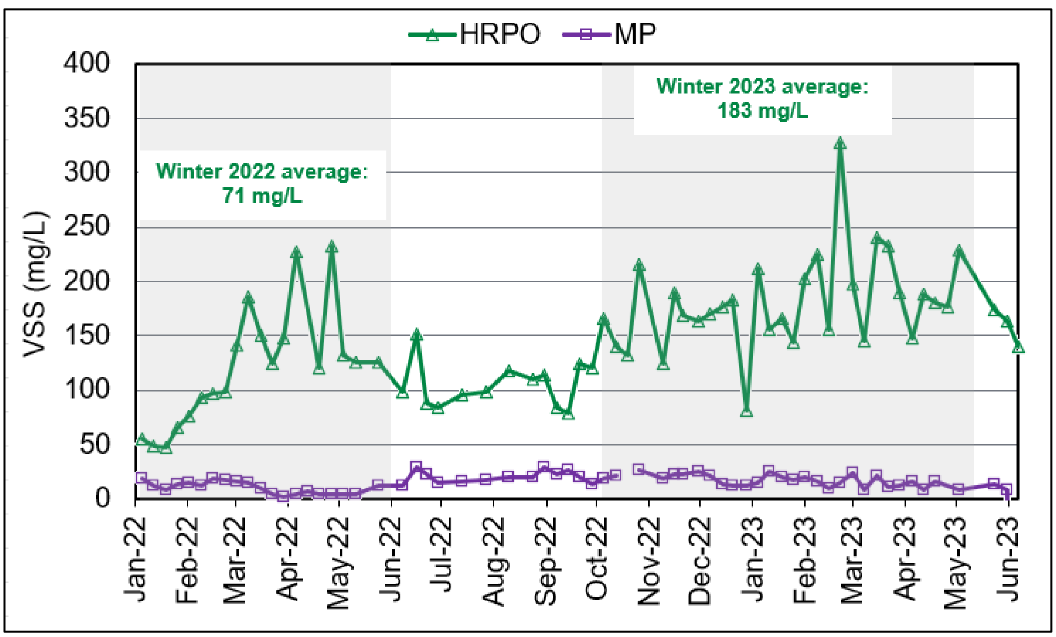
In conventional activated sludge, an HRT of 12 to 24 hours is required for nitrification in warm and cold weather, respectively. In this relatively short HRT, warm sewage does not cool as much (to ~15°C [59°F]) as it does in long HRT ponds (to near ambient temperature). Achieving cool water nitrification in activated sludge is helped by maintaining a high concentration of nitrifying biomass (via settled biomass return), for example, in the range of 3,000-4,500 mg/L volatile suspended solids (VSS). In cold ponds, presumably the long HRT helps compensate for the slower nitrification. Increasing raceway VSS concentrations and solids residence time should promote a higher nitrification rate, even if activated sludge VSS concentrations are not achieved. Thus, at Delhi, return of settled biomass from the settling basin to the outer raceway was arranged for long-term experimentation.

TASK 4: Test Set 1.3 — Biological Treatment Performance Data Collection in the Central Valley

Based on the biological principles governing nitrification and treatment data from the pilot-scale experiments (see Task 7), substantial increases in VSS concentration are necessary to meet the intended limit of <10 mg/L total N in the colder months. To achieve the desired rates of TAN removal in winter, solids concentrations in the HRPO may need to be increased to as high as 400-800 mg/L.

In response to these findings, various approaches to increasing the solids concentration in the HRPO were evaluated. Three approaches were devised and tested, first at the laboratory scale using reactors fed with water from the HRPO. The methods evaluated were selected based on their ability to be mimicked at full scale with only slight modifications to the operation of the existing treatment system. The most promising experiment indicated that returning a portion of the settled algae slurry from the ASP back into the HRPO could improve nitrification in simulated winter temperatures. Therefore, implementation of full-scale solids return was the next emphasis of the research effort. This was accomplished by connecting a pipe and shut-off valve into a junction with access to the pipeline that carried settled algae from the ASP to the drying beds. Results highlighting the VSS concentration during periods of solids return at full scale are shown in Figure 10, and the associated TAN concentration is shown in Figure 11.

Figure 10: Weekly Average Solids Concentration During Solids Return to the HRPO



Time series of weekly average VSS concentration in the HRPO and the MP from January 2022 to June 2023. The grey shaded areas indicate the period when solids were being continuously returned to the outer raceway from the ASP.

Source: Feldsien, 2024.

Following the first round of pumping solids into the HRPO starting in January 2022, the HRPO VSS concentration doubled from 50 to 100 mg/L within the first month. This general trend of increasing VSS continued through the spring, reaching a peak of 240 mg/L. In the summer, solids return was paused due to warmer weather and the associated increases in pond nitrification and N assimilation rates. During this period, from May to September 2022, the VSS remained steady at around 100 mg/L. So, the implementation of solids return resulted in the winter and spring VSS concentrations matching or exceeding the typical average summer concentration by as much as twofold.

In October 2022, slurry return pumping to the HRPO was resumed with even longer pulses of solids return than in the previous year, attempting to build up solids concentrations before the beginning of the cold months. This operational change successfully maintained VSS in HRPO between 150-250 mg/L for almost the entirety of the winter, with an average of 183 mg/L. Importantly, the returned solids did not affect downstream removal as evidenced by the solids concentration in the MP never exceeding 30 mg/L. The VSS in the MP annually averaged only 15 mg/L over the duration of the study period.

In summary, compared to the previous winters, there was an almost threefold increase in average solids concentration for the winter months in 2023 (Table 2). Additionally, the overall annual average solids concentration in 2023 was about 50 percent greater than in 2021 and 30 percent greater than in 2022.

Table 2: Annual and Seasonal Average VSS Concentration in the HRPO

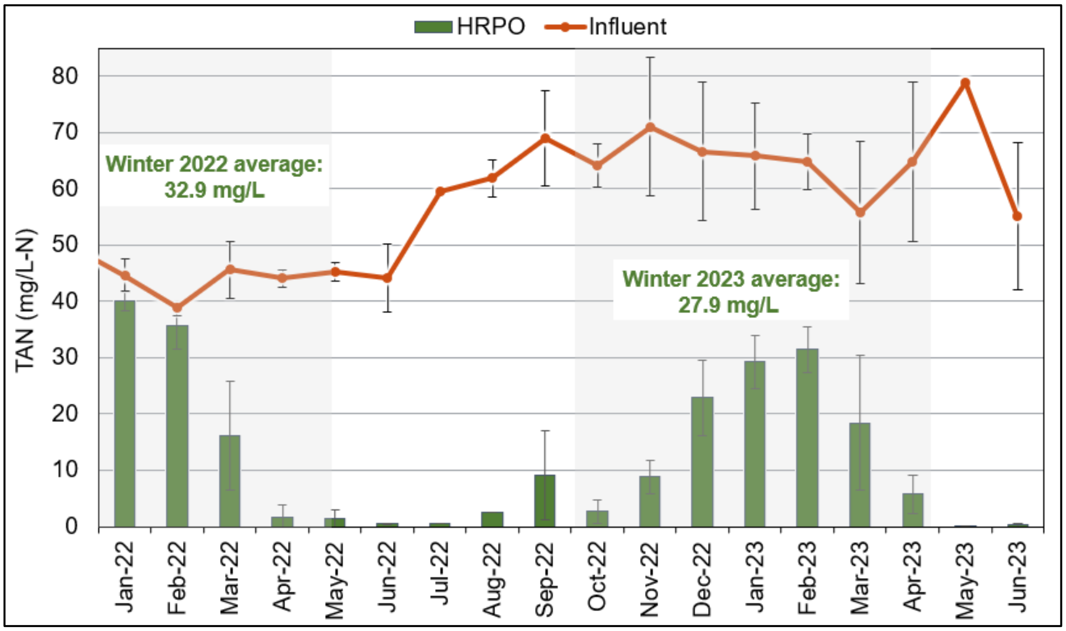
Season	2021 VSS, mg/L	2022 VSS, mg/L	2023 VSS, mg/L
Winter	68	71	183
Spring	79	145	187
Summer	111	106	178
Fall	106	142	NM
Annual Average	**91**	**116**	**172**

Seasonal average of VSS concentrations calculated from weekly average data collected from November 2020 to June 2023. NM is Not Measured; no data were collected during the Fall of 2023. Winter = December-February, Spring = March-May, Summer = June-August, Fall = September-November.

Source: Feldsien, 2024.

Alongside the successful implementation of increasing VSS concentration in the HRPO, TAN removal also improved in the 2022-2023 winter in comparison to 2021-2022. Comparing the average TAN concentrations in HRPO during each winter (Figure 11), there was a 5-10 mg/L decrease from 2022 to 2023. Simultaneous to this decrease in effluent TAN was an upward trend in the influent TAN. Further comparison of this year-to-year difference indicated a 34-percent increase in wintertime TAN removal in the 2022-2023 winter. Because HRPO VSS concentration was the only variable being actively manipulated within the full-scale system from one year to the next, the VSS increase was hypothesized to be the most likely factor responsible for the improved nitrification, especially because the association was already demonstrated in the controlled lab-scale experiments.

Figure 11: Monthly Average TAN Concentration During Solids Return to the HRPO



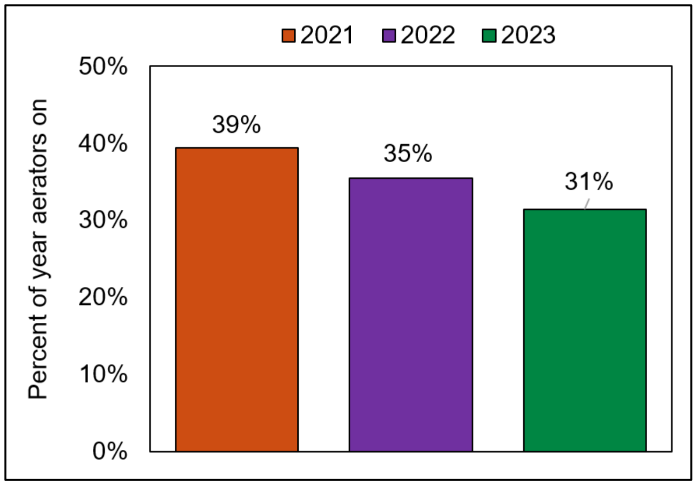
Time series of monthly average TAN concentration in the influent to the facility and the HRPO from January 2022 to June 2023. The grey shaded areas indicate the period when solids were being continuously returned to the HRPO from the ASP. Average concentration labels are for January-March 2022 and 2023. Error bars represent one standard deviation from the mean.

Source: Feldsien, 2024.

These results suggested that increasing the VSS improves TAN removal. However, despite the nearly threefold increase in VSS, TAN concentrations in winter months still exceeded the 5-mg/L target.

Even so, the optimizations developed and tested during this project had positive impacts on the energy efficiency of the facility. Analysis of data collected from 2020 to 2023 revealed that aeration demand from the brush aerators in the HRPO was decreased (Figure 12), and there were improvements to treatment performance metrics like VSS and TAN concentrations. Comparing the data by year from November 2020 to June 2023, the percentage of the year the aerators in the HRPO were on was reduced by 10 percent from 2021 to 2022 and by 20 percent from 2021 to 2023.

Figure 12: Aeration Demand Decrease Resulting From Optimization



Percentages represent the annual number of hours the aerators were on in the HRPO out of total hours in a year for 2021, 2022, and 2023. Operational modifications of the raceway ponds process at the full-scale wastewater treatment facility in Delhi, CA resulted in yearly decreases in the total time that aeration was needed.

Source: MicroBio Engineering Inc.

TASK 5: Test Set 1.4 — High Flux — Recycled Water Filtration Studies

MBE installed an ultrafiltration (UF) membrane filtration skid with two 40-m^2 PVC hollow fiber inside-to-out crossflow ultrafiltration cartridges at the Meadowbrook Wastewater Treatment Plant (MWWTP) in Templeton, CA on a concrete pad near the existing pressurized sand filter (SF) vessels (Figure 13).

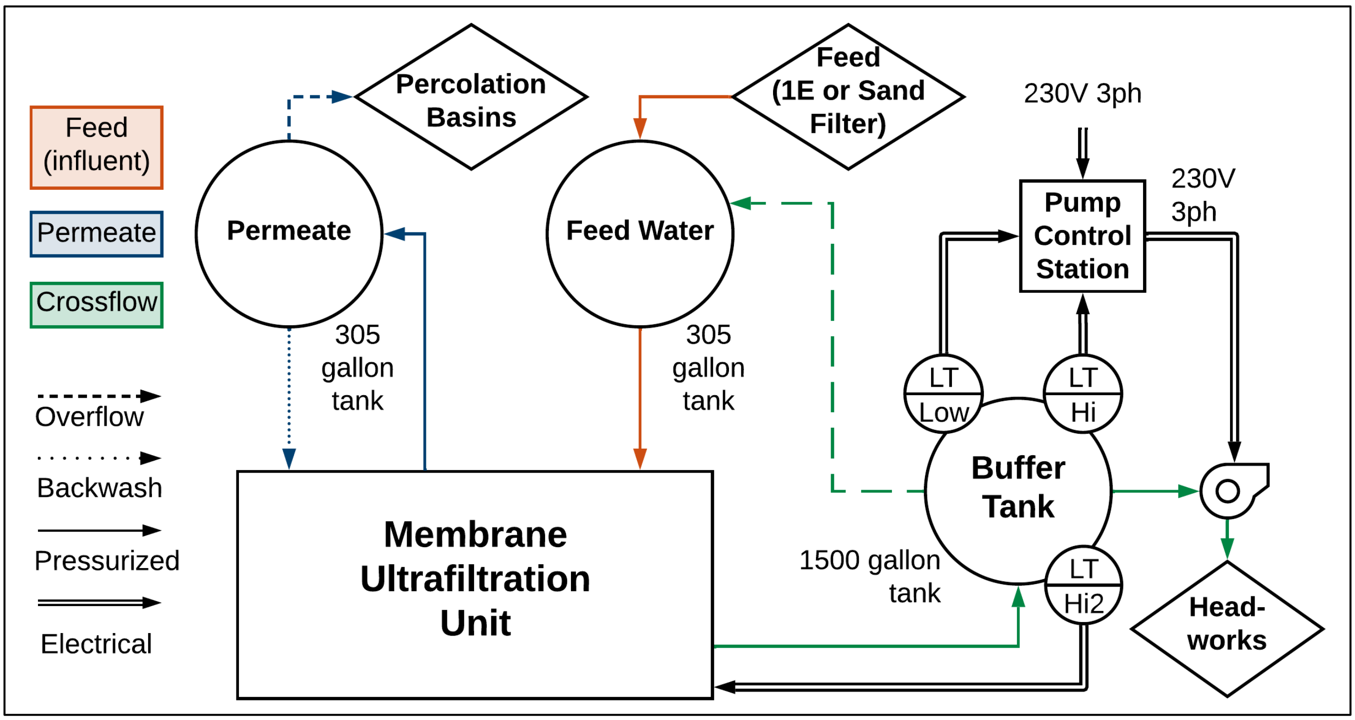
Figure 13: UF Pilot Skid at the Meadowbrook WWTP

A turbidimeter and other testing equipment were used for instantaneous measurements, while samples were also collected for laboratory analysis.

Source: MicroBio Engineering Inc.

MWWTP staff poured the equipment pad and provided an effluent hookup to pond 1E (the second-to-last pond in the treatment train). A prevailing wage electrician expanded the power supply to 480 volts and grounded the filter unit. MBE constructed a heavy-duty equipment shelter over the membrane filtration skid, along with peripheral equipment and tanks necessary for operation. A major operational concern was discovered during shakedown trials in late 2019, when the backwash from the MWWTP's sand filter line over-pressurized the UF crossflow and blowdown return line, creating a blockage that would trigger an automated shutoff. Though rare, it prevented performing trials lasting longer than a day. A buffer tank plus booster pump solution was developed and installed, creating the final configuration in March 2020 (Figure 14).

Figure 14: Simplified UF Pilot Process Flow

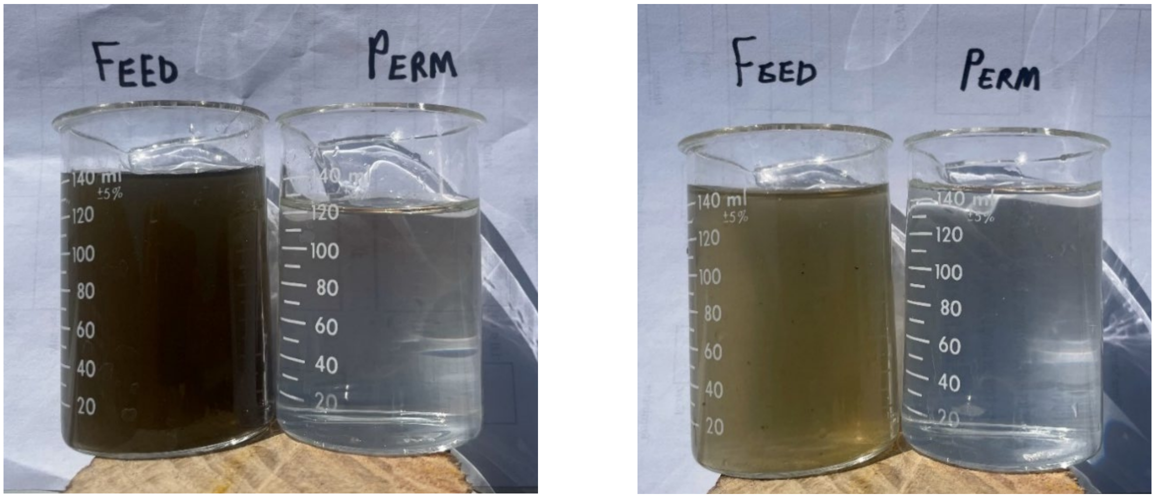


Source: MicroBio Engineering Inc.

Midway through the first week-long trial, a shelter-in-place order was issued in response to COVID-19 in California. After the project team returned to the site, it found the pond 1E effluent to be unusable, as the MWWTP was facing extreme solids buildup in this pond. An edge-case test was conducted using a feed water that was up to 123 NTU (NTU = nephelometric turbidity units, a measure of water clarity; for context, a typical UF feed is <50 NTU).

The permeate (filtered water) from the trials had <0.1 NTU (Figure 15). While this trial was able to produce low-turbidity permeate, it achieved only a 15-percent recovery ratio (the ratio of clean filtered water flow to feed water flow). Although fouling was reversible by backwashing, the energy use was high, and the recovery was too low for long-term operation. The trial did provide insights into the unit's ability to produce high-quality effluent despite influent quality fluctuations.

Figure 15: Beaker Photos Showing Edge-case Test Results with UF Pilot Skid at MWWTP



Left: the edge-case with ~200-mg total suspended solids per liter (TSS/L) feed and low turbidity permeate. Right: a high end of an average 40-mg TSS/L feed with permeate of similar quality to the edge case.

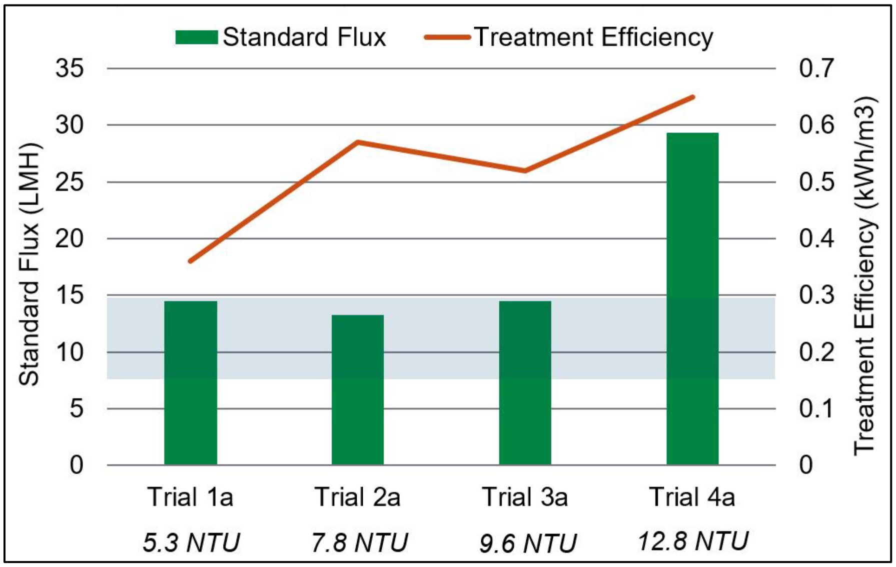
Source: MicroBio Engineering Inc.

MWWTP operators installed a tap into their SF-treated effluent line to provide an alternative feed source for the UF skid. A series of week-long runs were planned to test nine configurations of three variables: recovery ratio (permeate), feed flow, and backwash interval.

After four trials, the MWWTP operators took the sand filters out of operation for a renovation forecast to last 6-plus months, which eliminated the feed source.

While treatment quality was high (<0.2 NTU on average), energy efficiency was marginal at an average of 0.53 kilowatt-hours (kWh) per cubic meter (m^3) treated (~0.3 kWh/m^3 above baseline microfiltration technology). The low flux target of 7 liters of clean water produced, per square meter of filter, per hour (LMH) was exceeded during each run, and the averaged flux over the experiments was above the 11.1 LMH averaged target (Figure 16). The initial results indicated that the crossflow UF filter was not an energy-efficient option for the polishing of tertiary-level treated wastewater.

Figure 16: Standard Flux Compared With Electricity Consumed per Cubic Meter of Wastewater Treated



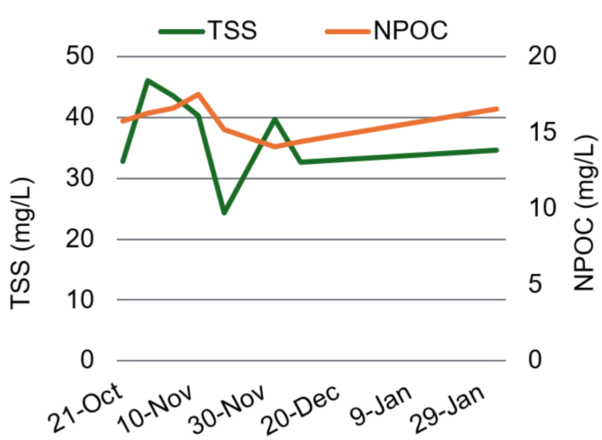
Note the increase in average feed turbidity with each new trial. The flux target range of 7.4 to 14.7 LMH is highlighted with the horizontal green shaded band.

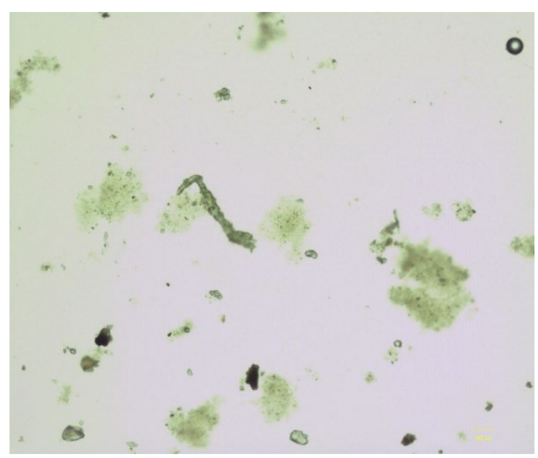
Source: MicroBio Engineering Inc.

As a next step, MBE created an experimental plan to test filtering of secondary-treated wastewater. Plans were made to flush out the existing 1E effluent control station (CS4) to remove sludge that had accumulated over the years. This station would then provide the secondary-treated wastewater feed source for Task 9.

To better characterize the 1E effluent, beginning October 10, 2020, samples were collected weekly from CS4 for analysis of TSS, VSS, Non-purgeable organic carbon or dissolved organic carbon (NPOC), and microscope images (Figure 17).

Figure 17: Results of CS4 Grab Sample Collection





Grab samples were taken from the weir overflow. The 1E effluent that fed the UF skid was piped from the bottom of CS4 — where sludge could build up if not run in free flow conditions. The micrograph shows mainly bacterial flocs binding together some small single-celled spheroidal microalgae.

Source: MicroBio Engineering Inc.

Grab sample results indicated that effluent from pond 1E (taken from CS4) would be an ideal candidate for testing crossflow filtration in Task 9. The 1E pond effluent had a feed quality that most dead-end or outside-in filters would struggle with (avg TSS = 37.3 mg/L), while not exceeding 100 mg/L. The dissolved organic carbon (a.k.a. non-purgeable organic carbon, NPOC) in 1E pond effluent could, however, have additional potential as a fouling agent.

TASK 6: Test Set 2.1 — Pilot System Configuration for Selected Effluent Treatment

Two types of wastewaters were available at the SLO WRRF: primary clarifier effluent (PE) and reclaimed wastewater (RWW). Most settled solids were removed from PE, but the fine particulate and dissolved organic matter concentrations were still high. RWW was fully treated by bacterial oxidation, granular media filtration, chlorine disinfection, and de-chlorination.

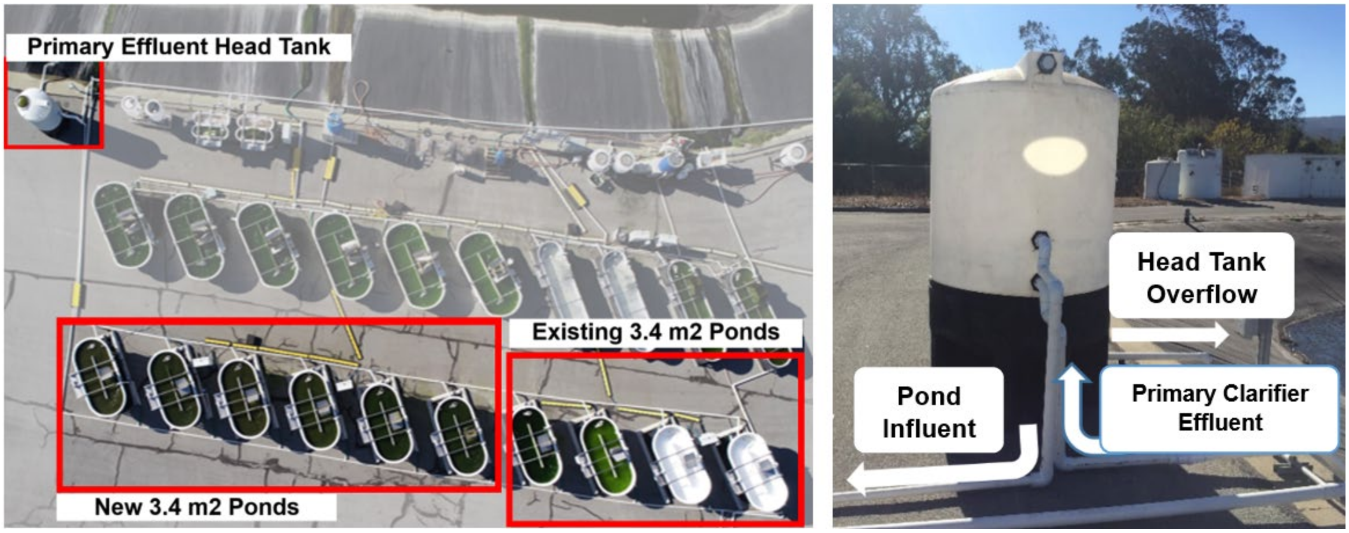
These two types of wastewaters are appropriate for different applications of treatment technology. Testing of PE treatment would represent undeveloped "greenfield" sites, such as a new housing development. RWW testing would support development of systems to remove nitrogen and/or phosphorus from the effluent of existing secondary treatment plants.

PE was selected for the raceway pilot studies at the SLO WRRF because PE better represents the water fed to the full-scale raceways at Delhi. Technology improvements at pilot scale would then be more easily scaled up. Additionally, building greenfield raceway facilities to treat PE would provide greater electricity savings compared to building facilities only to remove nutrients, which better supports the goals of the California Energy Commission's Electric Program Investment Charge program. In addition, treatment of PE generates more biomass for use as fertilizer or a biofuel feedstock.

Following the selection of PE as the influent to the pilot systems, the facility was reconfigured to provide primary effluent to ten instrumented pilot raceways. The PE was pumped from an equalization basin of the SLO WRRF. For an initial period, the PE from this basin was sampled along with PE collected directly from the effluent of the primary clarifier tanks. Comparing the water quality of the two sample sites, the samples were virtually identical in terms of the nutrient concentrations (nitrogen, phosphorus, and organic carbon), but the PE from the basin contained slightly more grit.

To prevent this grit from damaging automatic valves, a 1,000-L above-ground, cone-bottom tank was installed to receive the equalization basin flow. This tank served as both a settling tank and a constant head tank to feed the raceways by gravity. The tank (referred to as the primary effluent head tank) was configured with two outlets (Figure 18, right). One was an overflow pipe to maintain the water level, with its flow returned to the equalization basin. The other head tank pipe carried the PE to the ponds. Flow to each pond was controlled with automatic valves, which opened briefly at 30-minute intervals to achieve the targeted hydraulic residence time. Flow was provided only during the day to roughly mimic the diel flow pattern in municipal sewers.

Figure 18: Pilot System Layout and Primary Effluent Head Tank Configuration at SURE! Field Station



Sources: [Left] Image adapted from Google Earth by MicroBio Engineering Inc.
Source: [Right] MicroBio Engineering Inc.

TASK 7: Test Set 2.2 — Operational Optimization Experiments of Selected Effluent Treatment at Pilot Scale

Similar to the operational optimization process that occurred at the full-scale facility in Delhi, the initial work at the pilot-scale facility involved determining the best settings for the aerators in the raceway ponds to provide enough oxygen for organic matter and ammonium oxidation. Table 3 lists the aeration conditions that were trialed from March to December 2020.

Table 3: Summary of Aeration Optimization Experiments in 1,000-L Raceway Ponds

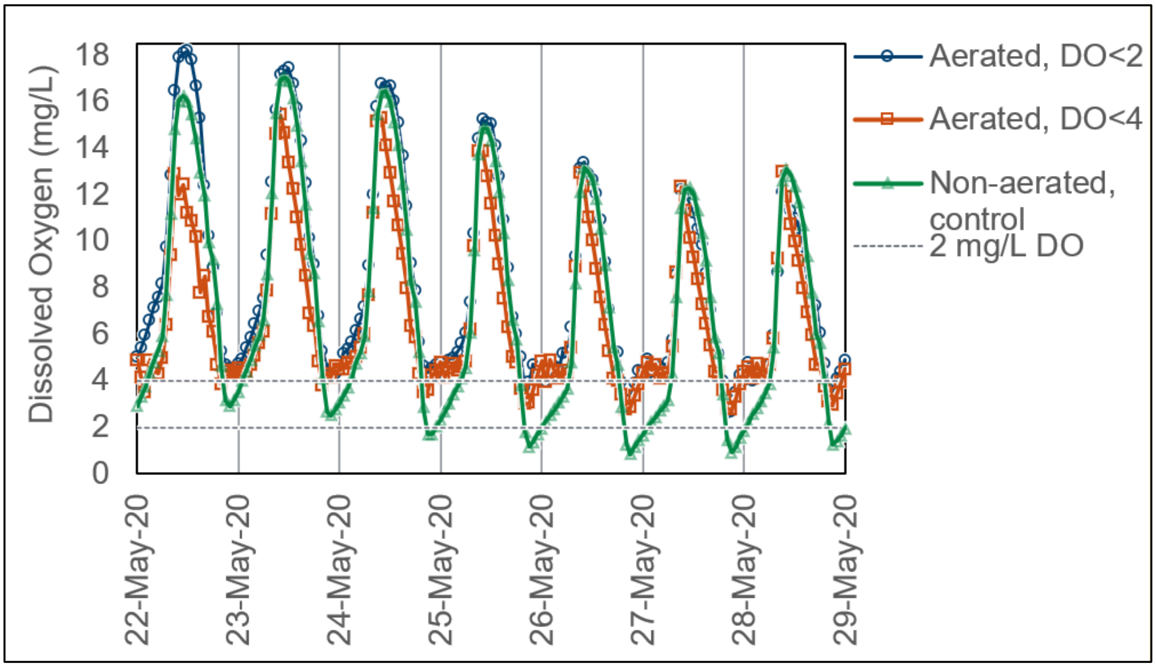
Dates	Pond Set 1	Pond Set 2	Pond Set 3
3/19/20 – 7/20/20	Aerated if DO<2 mg/L	Aerated if DO<4 mg/L	Control (no aeration)
7/21/20 – 10/6/20	Aerated if DO<2 mg/L	Aerated if DO<2 mg/L	Control (no aeration)
10/7/20 – 12/7/20	Control (no aeration)	Aerated if DO<2 mg/L	Aerated if DO<4 mg/L, from 1 pm to 7 pm only

Experiments were conducted using algae-based, wastewater-fed pilot raceway ponds. The HRT was 4 days for all experiments. All ponds were fed semi-continuously with primary-clarified effluent.

Source: Lesne, 2024.

During the first experiment, data from the DO probes in each pond revealed that the hourly DO concentrations in all ponds followed the same general pattern of fluctuation (Figure 19). However, the two sets of ponds with aeration had, on average, 50 percent fewer hours per day below 2 mg/L than the non-aerated control ponds. These added hours of abundant DO should have, in theory, benefited any DO-limited aerobic microorganisms.

Figure 19: Hourly DO Concentration With Different Levels of Supplemental Aeration in 1,000-L Ponds

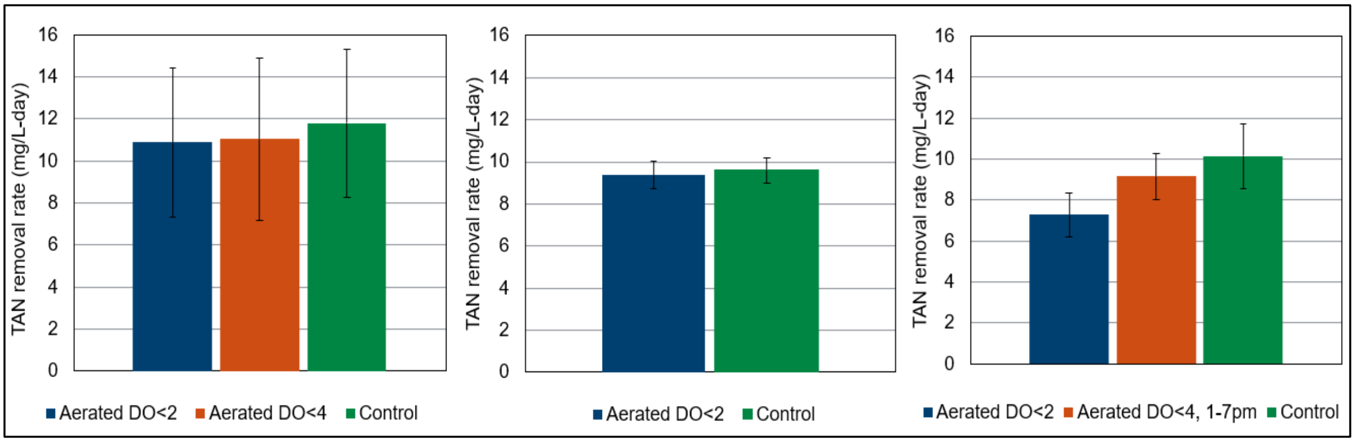


One week of hourly time series data for DO concentration in algae-based, wastewater-fed pilot raceway pond sets. The control set was provided with no supplemental aeration. The experimental sets were provided with in-pond aeration to maintain a minimum DO concentration of 2 or 4 mg/L. The dashed lines represent the minimum concentrations of 2 and 4 mg/L.

Source: Lesne, 2024.

While the inclusion of supplemental aeration in the pilot raceways successfully reduced the number of hours in a day with low DO and also increased the daily average DO compared to the control raceways, it did not result in an increase in the TAN removal rate. The data from the first two aeration experiments showed no difference in the average TAN removal rate regardless of the level of aeration (Figure 20). The data from the final experiment, which was intended to evaluate effects of supplemental aeration for limited hours only, showed that the non-aerated control ponds performed the same or better than aerated ponds. This result indicated that nitrifiers were not limited differently by DO under the aeration regimes. Preventing the night hours of DO<2 mg/L did not help nitrifier growth. A possible explanation is that the paddlewheels introduced enough oxygen to satisfy the nitrification demand, which might have been low during the cool nights. Supplemental aeration was deemed unnecessary for the PE-fed pilot studies. However, at full scale, paddlewheels are a relatively smaller source of dissolved oxygen.

Figure 20: TAN Removal Rate With Different Levels of Supplemental Aeration in 1,000-L Ponds



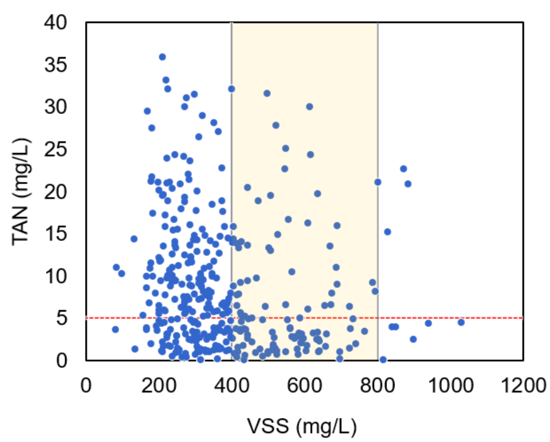
Comparison of overall average TAN removal rate (in mg of TAN removed per liter per day) in algae-based, wastewater-fed pilot raceway pond sets with different levels of supplemental aeration. Error bars represent one standard deviation from the mean.

Source: Lesne, 2024.

TASK 8: Test Set 2.3 — Biological Treatment Performance Data Collection of Selected Effluent Treatment at Pilot Scale

Along with solids residence time, VSS concentrations of algal-bacterial biomass should be related to nitrification rates. An analysis of all the pond VSS concentration and pond TAN concentration data from 2020 to 2022 (Figure 21) illustrates a visually apparent threshold VSS, above which many of the samples have TAN <10 mg/L. This threshold is likely dependent on several other factors, including, but not limited to, temperature, HRT, and the general ecology of the ponds. VSS concentrations that are apparently effective for nitrification range from 400 to 800 mg/L.

Figure 21: Effluent TAN Concentration Versus VSS Concentration in 1,000-L Ponds



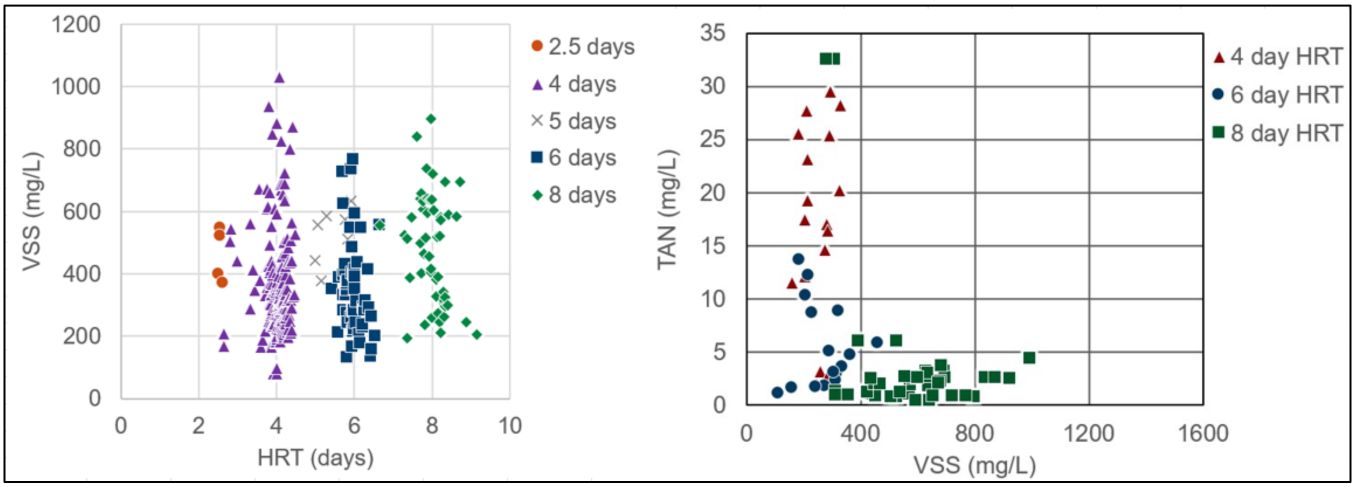
The dashed red line represents the target TAN concentration of 5 mg/L to meet nitrogen removal requirements of <10 mg/L total nitrogen (TN). The yellow shaded box is highlighting the window where TAN concentrations tended to be lower, based on visual analysis of the scatterplot data.

Source: Lesne, 2024.

The HRT of the raceways would be expected to affect TAN removal. Increased HRT allows more time for nitrifiers to convert TAN to nitrate, and it might have also allowed an increase in VSS concentration due to cell accumulation. To better understand the relationship of HRT to TAN removal, a range of HRTs was maintained during the project.

The following HRTs were tested: 2.5, 5, 6, and 8 days. Ponds with 4-day HRTs were designated the control or baseline. Comparing data for HRT and VSS concentration across the entire project (Figure 22, left), the range of VSS concentrations did not differ substantially among the HRTs. However, considering TAN and VSS concentrations for the different HRTs of 4, 6, and 8 days (Figure 22, right), the threshold VSS concentration for reliable TAN removal was ~400 mg/L, matching the interpretation of the full-study cumulative data of Figure 21.

Figure 22: VSS Concentrations Versus HRT in 1,000-L Ponds

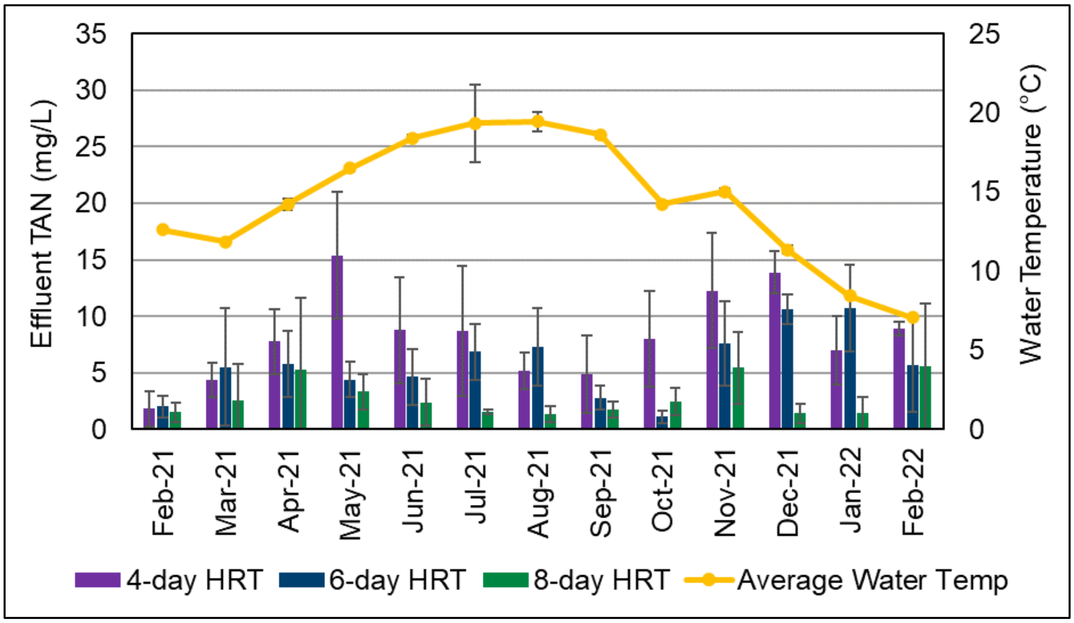


Two different graphical analyses are shown to demonstrate the relationship between VSS concentrations and HRT in algae-based, wastewater-fed pilot raceway pond sets. Left, suspended solids concentrations in response to 2.5-, 4-, 5-, 6-, and 8-day HRTs based on data from 2020 to 2022. Right, effluent TAN concentrations in response to suspended solids concentrations grouped by HRT.

Source: MicroBio Engineering Inc.

In addition to the VSS threshold, HRT did appear to correlate with TAN removal. The monthly averages for TAN concentrations leaving each of the pond sets over the span of a full year (Figure 23) show that the pond sets with the longer residence times were able to treat the wastewater to 10 mg/L of TAN or less for a full year, even in the winter when water temperatures were cooler. The pond set with an HRT of 8 days was able to achieve effluent TAN concentrations of less than 5 mg/L on a monthly average for the entire year. This provides evidence that, at the pilot scale, monthly discharge limits can be met using the raceway ponds, even in the winter.

Figure 23: Annual Summary of Effluent TAN Concentrations Versus HRT in 1,000-L Ponds



Annual data for monthly average TAN concentration in algae-based, wastewater-fed pilot raceway pond sets with varying HRTs from 2021 to 2022. Monthly average water temperature is also displayed to illustrate the seasonality of weather conditions. Monthly average water temperature was calculated by averaging data collected from each pond. Error bars represent one standard deviation from the mean.

Source: Lesne, 2024.

TASK 9: Test Set 2.4 — High Recovery — Recycled Water Filtration Studies

Tubular, inside-to-out, UF membrane filtration was hypothesized to have lower fouling rates than outside-to-in microfilters. This would allow the filter to manage high incoming suspended solids.

Task 9 used a membrane filter pilot setup identical to that at the end of Task 5 but with a flushed 1E CS4 and pipe providing the filter feed. (1E is the second-to-the-last pond in the MWWTP treatment system.) The first trials in this task repeated weeklong experiments similar to those of Task 5, where recovery ratio, feed flow, and backwash interval were controlled (Table 4). A system curve was developed to identify the lowest transmembrane pressure (TMP) that intersected with the highest permeate production and reduced backwashing (an energy-intensive process that creates downtime and produces concentrated waste).

Table 4: 7-day Trial Experimental Plans — UF Skid Configurations

Trial Name	Week of (2021)	Feed Flow (m^3/hr)	Recovery Ratio (%)	Backwash Interval (min)
1b	2/16	6	16	30
2b	2/23	5	20	45

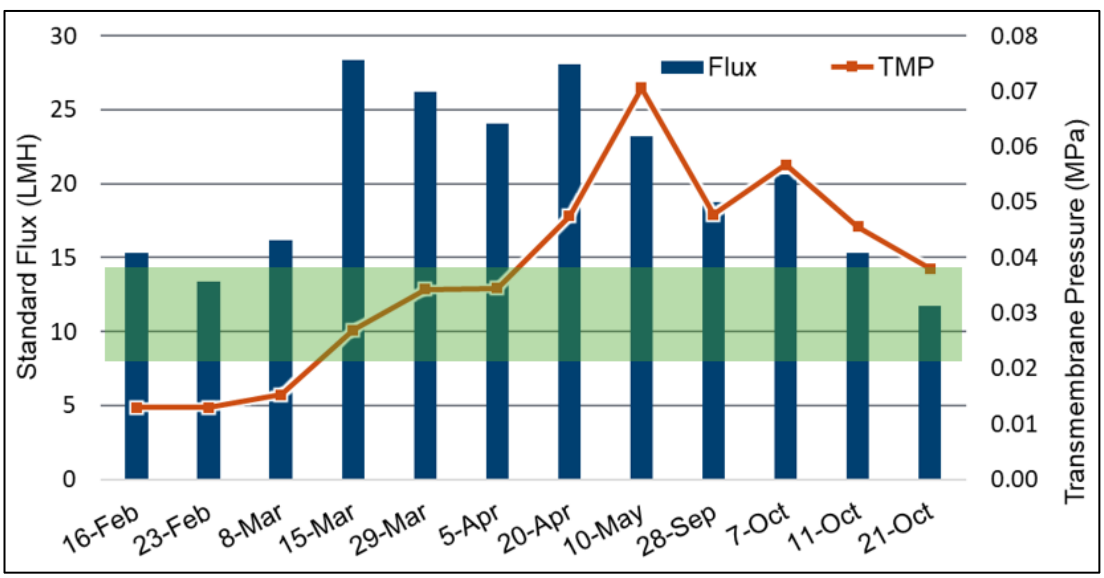
Trial Name	Week of (2021)	Feed Flow (m^3/hr)	Recovery Ratio (%)	Backwash Interval (min)
3b	3/8	4	25	60
4b	4/5	12	16	45
5b, 5c	3/29, 9/28	10	20	60
6b	3/15	8	25	30
7b, 7c	4/20, 10/7	18	16	60
9a	5/10	12	25	45
10a	10/11	4	35	30
11a	10/21	4	30	45

MBE performed a full 4-hr clean-in-place operation between each trial.

Source: MicroBio Engineering Inc.

In total, 12 weeklong trials were conducted, identifying the maximum flux possible (standard flux: Js = ~28 LMH, corrected for feed temperature) and an average sustained standard flux of 25 LMH. Increasing the feed flow in the later trials served only to raise transmembrane pressure with a negligible increase in flux. The ideal operating point was determined to be a feed flow of 130 LPM, a recovery ratio of 25 percent, and a backwash interval of 45 minutes (Figure 24).

Figure 24: Standard Flux and Transmembrane Pressure from Each 7-day Trial with UF Skid



The flux target range of 7.4-14.7 LMH is highlighted with the horizontal green shaded band. The trial for the week of March 15 identified the ideal operating conditions for high flux and reduced TMP.

Source: MicroBio Engineering Inc.

Sustained month-long operation in the ideal operating conditions configuration (identified above) was planned to generate a pilot data set for the techno-economic analysis (TEA)/life cycle assessment (LCA). Midway through this run, it became clear that feed flow was being restricted as the prefilter and centrifugal feed pump were being clogged by hairs and synthetic fibers from the 1E effluent. This buildup artificially inflated electricity consumption as the pump impellers fouled and a higher pressure was necessary to force the flow past the pre-filter. MBE built and installed a parabolic screen and in-line 300-micrometer (μm) wye filter (an in-pipe filter) to address this problem, but continuous operation was still noticeably affected by pieces that passed through (Figure 25).

Figure 25: Evidence of Fouling Within the UF Skid Components

Left: the parabolic screen installed with continuous flow to collect the fibrous debris in 1E effluent. Right: the feed pump, with the impeller vanes filled by fibers caught on the sharp edges.

Source: MicroBio Engineering Inc.

An initial model built around the results from the week-long trials indicated that even the best operating point could not compare to existing outside-in technology — after correcting electricity consumption around the filter TMP rather than the fouled feed pump power demand. An outside-in microfiltration unit treating municipal wastewater pond effluent was used for comparison to the UF unit (Table 5).

Table 5: Comparison of UF and MF systems, With Similar Feed Quality

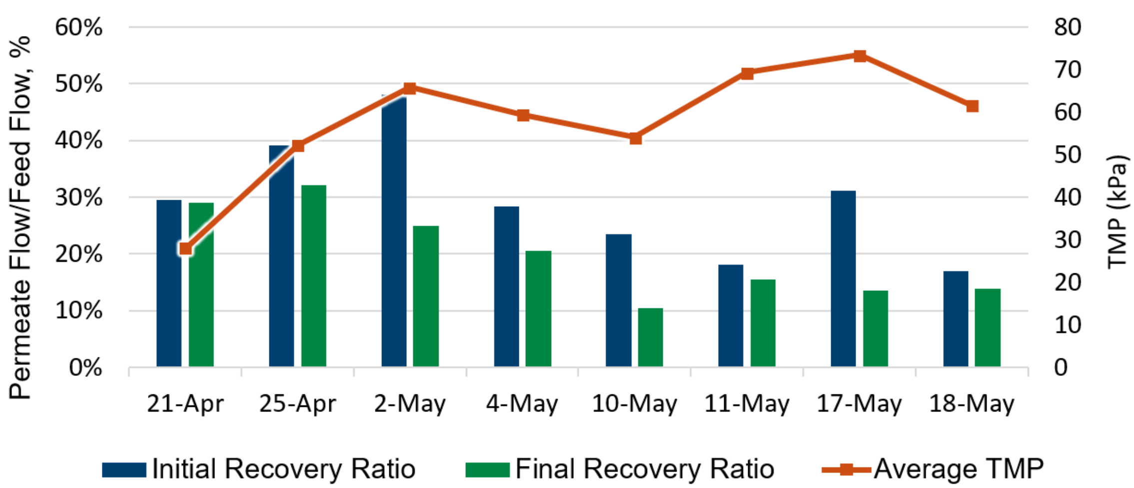
Parameter	Crossflow Ultrafilter Pilot	Outside-in Microfilter	Units
Standard Flux	25	10	LMH
TMP	35	1	kPa
Recovery Ratio	28	97	%
Electricity Use	0.60	0.15	kWh/m^3

Feed quality for both filtration systems was 20-40 mg TSS/L and ~5-15 mg NPOC/L. LMH = liters of clean water produced per square meter of filter per hour; kPa= kilopascals (unit of pressure measurement); kWh/m^3 = kilowatt-hours used per cubic meter of clean water produced.

Source: MicroBio Engineering Inc.

Though the UF pilot treated a wider range of suspended solids with a higher flux, the TMP and recovery ratio could not compete with the MF unit. After accounting for the UF crossflow recycle, the average TMP/LMH of permeate produced from the UF filter was 50 times higher than that of the MF filter — which is high enough to negate chemical consumption comparison. An updated experimental plan was developed to push the recovery ratio as high as possible to reduce the costs associated with recycling the crossflow. These experiments were run as one-day operations to reduce the effect of prefilter clogging on pressure and feed flow. 1E effluent results confirmed the initial weeklong trials — maximum sustained recovery of secondary-treated water remained around 30 percent at best. A 50-percent recovery trial was planned at a TMP of ~0.07 megapascals (Mpa, a unit of pressure measurement) using filtered effluent from the renovated pressurized sand filters on May 2, 2022. After one day, the recovery dropped back to 25 percent, and further trials identified this as irreversible fouling in the cartridges. Chemical cleaning and backwashing were unable to restore the cartridges, as TMP would rise to extreme levels even at a low flow and recovery ratio (Figure 26). No further work was conducted with this filter unit due to its poor performance.

Figure 26: Initial Versus Final Recovery Ratios After 24-hr Operations Compared to Average TMP



Note the extreme drop from ~45% to 25% on May 2 and how, even with low recovery ratios, a low TMP was never restored.

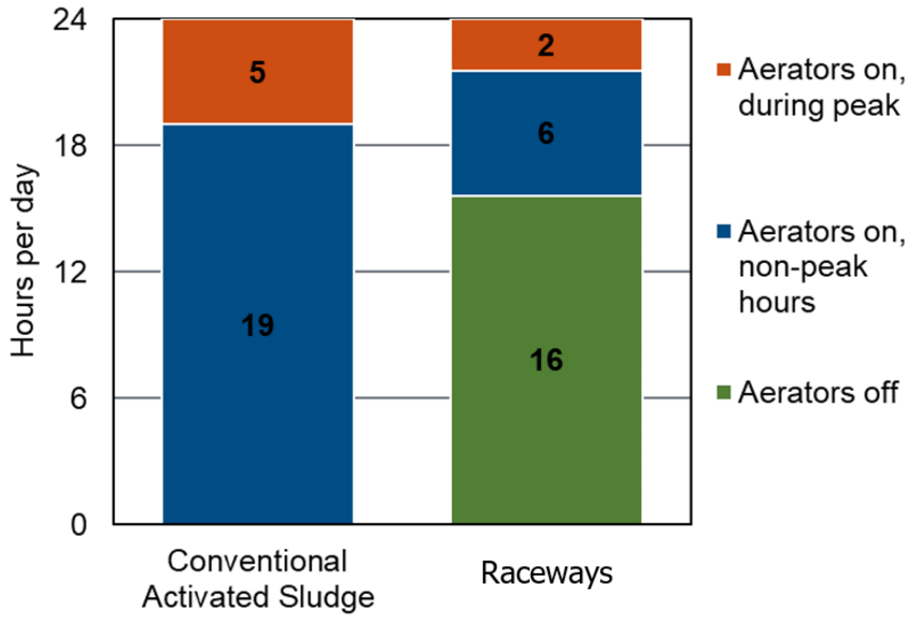
Source: MicroBio Engineering Inc.

TASK 10: Project Benefits

Energy Savings Benefits

Over the three-year project, collaboration with the operators at the full-scale facility in Delhi enabled adjustments to the time that aerators were on in the HRPO. Weekly sampling and analysis of the effluent from each step facilitated weekly decision-making that resulted in reductions in overall aeration year over year (see Figure 12). In addition, experiments on the raceway ponds process at the full-scale wastewater treatment facility in Delhi, CA more reliably removed nitrogen with limited power use during peak demand and less time overall compared to activated sludge systems (Figure 27).

Figure 27: Daily Average Hours of Aeration Required for Raceway Ponds Compared to Conventional Activated Sludge

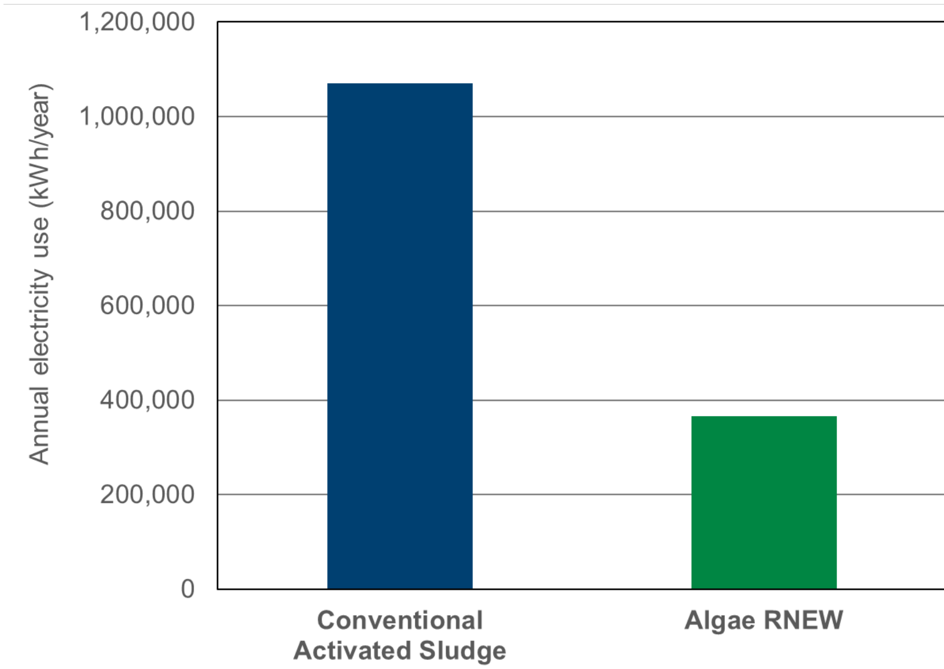


Daily average aeration for the raceway ponds process was calculated based on the annual average time that aerators were on in the HRPO at the Delhi CWD WWTP from 2020 to 2023, combined (data provided by the Delhi CWD). For the conventional activated sludge system, aerators were assumed to be on 24 hours per day, as is required in these systems.

Source: MicroBio Engineering Inc.

Because of this ability to provide treatment with limited use of aeration, the electricity consumption of raceway ponds is much lower than a facility of the same size using activated sludge. In fact, implementation of raceway ponds with optimization could result in up to a 66-percent reduction in annual energy use for a wastewater treatment facility (Figure 28). Based on the data collected, the savings in energy consumption for a 0.6-MGD facility like the Delhi CWD WWTP was projected to be about 700,000 kWh annually.

Figure 28: Annual Energy Use for Conventional Activated Sludge Compared to Raceway Ponds at 0.6 MGD



Annual energy use estimates are shown at the scale of 0.6 million gallons of wastewater treated per day (MGD). Facility size is scaled to match the size of the Delhi facility. Energy use estimates are based on the LCA completed by MBE. Site-specific equipment and electrical data were provided directly by the Delhi CWD WWTP.

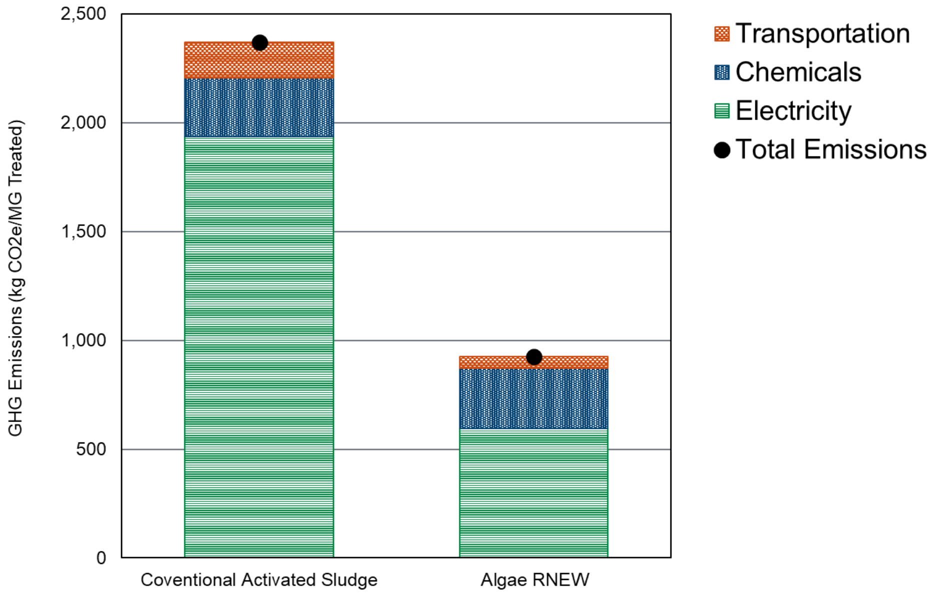
Source: MicroBio Engineering Inc.

Greenhouse Gas Lifecycle Assessment of the Proposed Technology

An LCA compared modeled estimates of total greenhouse gas (GHG) emissions for a conventional activated sludge (CAS) facility treating 1 MGD to the same size raceway ponds facility. The estimate included emissions associated with the transportation of residual solids, chemical/material use, and electricity consumption (Figure 29).

The total GHG emissions were 2,371 kilograms of carbon dioxide equivalent per million gallons treated (kg CO_2e/MG) for CAS and 925 kg CO_2e/MG for the raceway system. For both systems, electricity consumption represented the largest contribution to total GHG emissions and was 2.5 times greater for CAS than for raceway ponds. In general, indirect GHG emissions associated with the upstream production and sourcing of chemicals resulted in the second highest contribution to overall emissions and were similar in both systems. Transportation of the biosolids/algae biomass generated during wastewater treatment operations contributed the lowest emissions and was more than 2 times greater in the CAS system. These results indicate that the raceway ponds technology has the potential to significantly reduce the overall environmental burden of wastewater treatment for small municipalities located in the US when compared to the option of upgrading to conventional activated sludge.

Figure 29: GHG Emissions for CAS Compared to Raceway Ponds



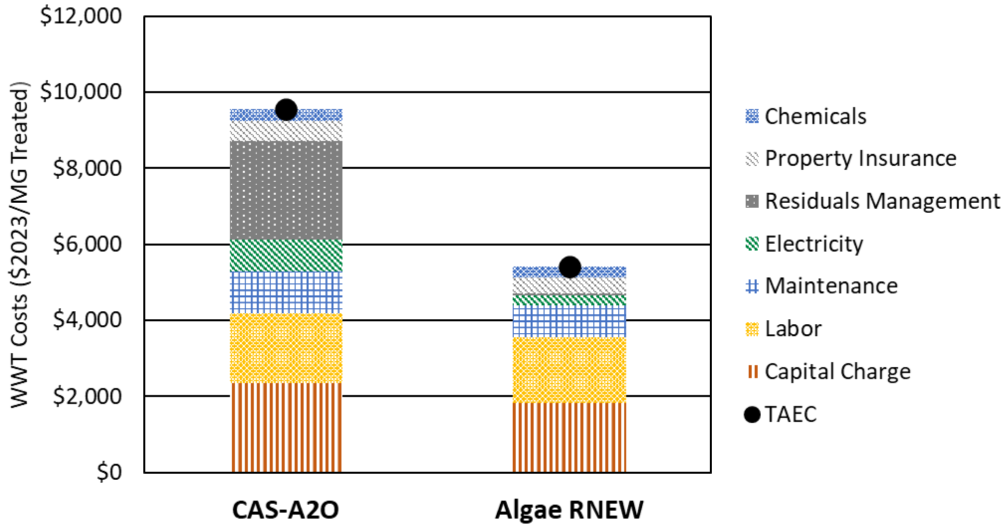
LCA results are presented as a function of volume of wastewater treated. Due to the high uncertainty associated with quantifying process-based emissions of GHGs from both CAS and algae pond systems, fugitive methane and nitrous oxide emissions were excluded from this analysis. Similarly, embodied GHG emissions associated with construction materials, including, for example, concrete, metal piping, and electrical equipment, were omitted to simplify the scope of the LCA. Fixed GHG emission intensity factors for electricity generation (specifically, the US national average grid), chemicals, and transportation were obtained from ecoinvent and GREET lifecycle inventory databases.

Source: MicroBio Engineering Inc.

Other Project Benefits

Results of the TEA indicated that the raceway ponds technology is also an economically attractive option for communities seeking to upgrade their existing facilities or construct new greenfield facilities to meet increasingly stringent nitrogen discharge limits (Figure 30). Assuming a 20-year facility lifetime, the total annual economic cost of raceway ponds was slightly more than half the cost of CAS, with the largest cost savings coming from the initial capital expense, electricity, and residuals management or biosolids handling. Note that biosolids management for raceway ponds assumes hauling fees only, as the dried algae material can be sent to a recovery facility for upcycling as opposed to a landfill with associated tipping fees; landfill disposal is the case for many activated sludge plants if they do not have the option for land application.

Figure 30: Total Annual Economic Cost per Million Gallons Treated for CAS Compared to Raceway Ponds



TEA results are presented for a 0.6-MGD greenfield facility as a function of annual economic cost, assuming a 20-year facility lifetime, a 6-percent cost of capital and normalized per million gallons treated. Costs are given in 2023 US dollars.

Source: MicroBio Engineering Inc.

A total annualized economic cost (TAEC) was estimated considering all relevant capital and operational expenses introduced above. The lifetime of each facility was set to a 20-year operational period and the opportunity cost of capital was set to 6 percent, which are representative financial parameters for projecting the wastewater treatment economics of small municipalities. If not given, the maintenance and property insurance expenses were estimated as 4 percent and 2 percent, respectively, of the total capital expenses. Indirect costing factors, such as project contingencies and land purchase and preparation, were excluded from this analysis.

Although the modeled costs of labor were similar for both conventional activated sludge anaerobic-anoxic-oxic (CAS-A2O) and raceway ponds, another benefit of raceway ponds is the level of training required of its operators. As a modified pond system, raceway ponds require the chief plant officer to be a level II trained operator, whereas a similarly sized (0.6-MGD) CAS-A2O would require at least a level III operator to run the facility. Although not a huge difference in cost, lower-level staff may be more available in rural regions.

In summary, raceway ponds have benefits that outweigh the conventional counterpart of activated sludge from at least three perspectives. These benefits include approximately a 2.5 times reduction in emitted CO_2e, approximately a 50-percent cost savings, and operational savings in that operators with only a grade II certification are required to run the plant.

CHAPTER 4: Conclusion

The advancements made over the course of this project set raceway ponds on the trajectory toward providing a nature-based solution for municipal wastewater treatment that is particularly well suited for rural communities in need of conventional pond upgrades to meet lower nutrient discharge limits. It is a solution that uses less electricity, with lower associated GHG emissions, than traditional alternatives. Additionally, raceway ponds can be operated in a manner that uses less electricity during periods of peak demand, freeing up electricity for essential functions during these periods.

The accomplishments during this project also contribute to advancing environmental justice disparities, by working to develop low-cost solutions for underserved rural communities that often cannot afford the more intensive and costly upgrades. Raceway ponds provide an option to improve effluent water quality for about half of the cost of more traditional upgrades and with about a 67-percent reduction in associated GHG emissions.

Experiments investigating the treatment of municipal wastewater at bench, pilot, and full scale over the course of three years advanced the science and engineering of raceway ponds to simultaneously minimize effluent total nitrogen and minimize electricity demand. These experiments identified the minimum HRT, ideal algal-bacterial concentrations, and minimum DO concentration needed within the raceways to achieve effluent TN <10 mg/L on a year-round basis.

Results also indicated that, while inside-out crossflow ultrafiltration of a heavily loaded pond system was able to filter wastewater containing high suspended solids concentrations, outside-in microfiltration with air scouring will likely use less electricity despite its higher transmembrane pressure, due to its much higher water recovery ratios.

Initial investigations into market opportunities for adoption of raceway ponds suggest that there may be as many as 50 traditional pond facilities in California's State Water Board Region 5 (the Central Valley) that have recently or will be coming up for permit renewal in the next few years. These communities, and ones like them in other regions of California, are the most likely first adopters of raceway ponds and will be the focus of initial outreach initiatives.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition[3]
°C	Degrees Celsius — a unit of temperature
ASP	Algae settling pond — an earthen or concrete structure using gravity or sedimentation to remove settleable matter and turbidity from wastewater
Bioflocculation	A process in which removal of flocculants in water is achieved in the presence of microorganisms or biodegradable macromolecules released by them
Cal Poly SLO	California Polytechnic State University, San Luis Obispo
CAS	Conventional activated sludge — a secondary step of wastewater treatment involving biological treatment, wherein bacteria are concentrated and combined with vast amounts of oxygen to facilitate bacterial breakdown of nutrients like nitrogen and carbon
CAS-A2O	The conventional activated sludge anaerobic-anoxic-oxic process
CEC	California Energy Commission
cm	Centimeter — a metric unit of length, equal to one hundredth of a meter
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent — a unit of measure used to compare other greenhouse gases (GHGs) to carbon dioxide, regarding the effect of a given GHG on the environment Source: U.S. Energy Information Administration website (https://www.eia.gov/tools/glossary/index.php, accessed 2024)
CS4	Control Station 4 (1E effluent control station) — located at the Meadowbrook Wastewater Treatment Plant in Templeton, CA
CSU	California State University
CWD	County Water District
Denitrification	The biological reduction of nitrate (NO_3^-) and nitrite (NO_2^-) to nitrogen gasses (N_2O, N_2)
Diel	a full day-night cycle
Disinfected tertiary water (or reclaimed wastewater)	Wastewater that has been through primary and secondary treatment, has been filtered and then disinfected; it does not meet potable water standards.
DO	Dissolved oxygen
Effluent (or discharge)	The water leaving a particular treatment step or being discharged from a treatment facility; in this case, treated municipal wastewater

[3] Note: All term descriptions were created by MicroBio Engineering Inc. for this report, unless specified otherwise.

Term	Definition[3]
EPIC	Electric Program Investment Charge
FAC N	Facultative north — a facultative pond
FAC S	Facultative south — a facultative pond
Facultative pond (or facultative lagoon)	A secondary step of wastewater treatment that involves a deep pond (3-6 m deep) with an aerobic upper layer and an anaerobic lower layer
Flux	The filtration or flow rate (e.g., liters per hour) of water flowing through a filter membrane's surface area per unit area (e.g., square meter) of membrane
GHG	Greenhouse gas
Greenfield installation	A development or infrastructure project that is deployed where none has existed before. In contrast, a brownfield development is an upgrade or addition to an existing infrastructure.
GWh	Gigawatt-hour — a measure of electricity defined as a unit of energy; one gigawatt-hour equals one billion (1,000,000,000) watt-hours.
High-rate pond (or raceway pond)	A secondary step of wastewater treatment that involves a shallow (0.3-3 m deep), paddle-wheel-mixed pond
HRPI	Inner high-rate pond (raceway pond)
HRPO	Outer high-rate pond (raceway pond)
HRT	Hydraulic residence time
Influent	The water entering a particular treatment step or the water entering the facility as a whole; in this case, raw municipal wastewater
kg	Kilogram — the fundamental unit of mass in the International System of Units (SI), equal to one thousand grams
kPa	Kilopascal — a unit of pressure measurement; one kilopascal is equal to one thousand (1,000) pascals, which is the single unit of pressure.
kWh	Kilowatt-hour — a measure of electricity defined as a unit of energy; one kilowatt-hour equals one thousand (1,000) watt-hours.
kWh/m^3	Kilowatt-hours used per cubic meter of clean water produced (a wastewater treatment energy efficiency unit)
L	Liter
LCA	Life cycle assessment
LMH	Liters of clean water produced, per square meter of filter, per hour
LPM	Liters per minute
m^2	Square meter — a metric unit of measurement for area
MBE	MicroBio Engineering Inc.

Term	Definition[3]
MF	Microfiltration
MG (or MG treated)	Million gallons or million gallons treated — a unit of volume of treated wastewater
mg/L	Milligrams per liter
MGD	Million gallons per day — a unit of volume of treated wastewater over a specific unit of time
MP	Maturation pond (or polishing pond) — a tertiary step of wastewater treatment involving a shallow (1 m deep) pond that reduces bacteria and algae concentrations through zooplankton grazing and promotes natural disinfection processes
Mpa	Megapascal — a unit of pressure measurement; one megapascal is equal to one million pascals, which is the single unit of pressure.
MWWTP	Meadowbrook Wastewater Treatment Plant, in Templeton, CA
N	Nitrogen
Nitrification	The biological oxidation of ammonia (NH_4) to nitrite (NO_2) and ultimately to nitrate (NO_3)
Nitrogen assimilation	The uptake of inorganic nitrogen for the formation of organic nitrogen compounds like amino acids
NM	Not measured
NPOC	Non-purgeable organic carbon or dissolved organic carbon
NTU	Nephelometric turbidity unit — a measure of water clarity
PE	Primary effluent, or primary clarifier effluent, or primary clarified effluent — all three of these terms are used for the same wastewater product.
Percolation pond (or percolation bed)	A tertiary step of wastewater treatment involving a constructed impoundment or holding pond, the design and operation of which provide for treated water to be disposed of naturally through filtration into the ground and evaporative losses
Permeate	Filtered water that passed through a membrane filter in a water filtration process
pH	Power of hydrogen ions — a figure expressing the acidity or alkalinity of a solution on a logarithmic scale on which 7 is neutral; lower values are more acid and higher values are more alkaline.
Primary-clarified effluent	Wastewater that has undergone removal of large debris and grit as well as most settleable solids
Primary clarifier effluent	Wastewater that leaves the primary clarifier (a wastewater treatment unit or system)

Term	Definition[3]
Primary effluent	Wastewater that leaves a primary treatment stage
Productivity	The rate of generation of biomass — for pond algae, it is the algae biomass produced per area surface water per time
RWW	Reclaimed wastewater — in this report, it is wastewater that has been oxidized, filtered, and disinfected but does not meet potable water standards; it is sometimes referred to as "purple pipe" water.
SF	Sand filter
SLO WRRF	San Luis Obispo Water Resource Recovery Facility
SURE!	Sustainable Utilities Research and Education (https://ceenve.calpoly.edu/sure-program/)
TAEC	Total annualized economic cost
TAN	Total ammonia nitrogen
TEA	Techno-economic analysis, or techno-economic assessment
TMP	Transmembrane pressure
TN	Total nitrogen
TSS	Total suspended solids —particles nominally greater than 1.2 µm in size and suspended in water (i.e., not settled or floated to the water's surface). In TSS measurements, "total" means that the whole mass of the particles is measured, as dry weight.
UF	Ultrafiltration, or Ultrafilter
um or µm	Micrometer — a metric unit used to measure length, equal to one millionth of a meter; it is often shortened to "micron" or symbolized by "µm."
Volt	Volt — the unit used to measure electric potential difference; it is also known as voltage.
VSS	Volatile suspended solids — particles nominally greater than 1.2 µm in size and suspended in water (i.e., not settled or floated to the water's surface). In VSS measurements, "volatile" means that the combustible mass of the particles is measured. Volatile solids are commonly used to represent organic matter in water quality analysis.
Weir	An overflow structure that is used to alter flow characteristics and also allow for flow measurement; in this case, the weir is inside a large tank that allows the flow of wastewater to be detained, measured, and diverted to other treatment steps.
WWTP	Wastewater treatment plant

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Project Deliverables

The primary product deliverables in the key technical tasks are listed below.

TASK 2: Test Set 1.1 — Central Valley configuration and setup

- Site Modification Report

TASK 3: Test Set 1.2 — Operational optimization experiments

- Test Set 1 – Operational Optimization Experiments Report

TASK 4: Test Set 1.3 — Biological treatment performance data collection in the Central Valley

- Test Set 1 – Operational Model for Nitrogen Removal User's Manual
- Central Valley Treatment Report

TASK 5: Test Set 1.4 — High flux — Recycled water filtration studies

- Test Set 1 – Water Filtration Report

TASK 6: Test Set 2.1 — Pilot system configuration for selected effluent treatment

- Effluent Selection and Facility Reconfiguration Report

TASK 7: Test Set 2.2 — Operational optimization experiments of selected effluent treatment at pilot-scale

- Test Set 2 – Operational Optimization Experiments Report

TASK 8: Test Set 2.3 — Biological treatment performance data collection of selected effluent treatment at pilot-scale

- Test Set 2 – Operational Model for Nitrogen Removal User's Manual
- Selected Effluent Treatment Report

TASK 9: Test Set 2.4 — High recovery — Recycled water filtration studies

- Test Set 2 – Water Filtration Report

These project deliverables, including interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov.