CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Energy and Water in Food and Beverage Wastewater Reuse

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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 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.

Energy and Water in Food and Beverage Wastewater Reuse is the final report for the Energy and Water in Food and Beverage Wastewater Reuse project (EPC-18-010) conducted by Porifera 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 CEC at ERDD@energy.ca.gov.

ABSTRACT

Food and beverage processors are looking for solutions to treat high-starch wastewater that will help offset costs and allow them to remain market competitive. Forward osmosis is a water separation process where water travels across a semipermeable membrane. Forward osmosis has unique advantages for food and beverage applications because it can operate reliably when processing challenging liquids that quickly clog or foul other types of membrane processes, such as reverse osmosis that are pressure driven. High starch waste represents a new frontier for membrane-only systems like the Porifera's Forward Osmosis Recycler.

This Project demonstrated that the Porifera's Forward Osmosis Recycler system (optimized for high starch content) reduced energy, reduced chemicals, and reduced the maintenance required for reuse of hard-to-treat industrial wastewaters. In addition, it produces exceptionally clean water, requires a smaller footprint to operate, is easy to scale in size, has a wide pH operating range, and no biological treatment is required. As far as the waste stream, no brine disposal is needed, no waste that is produced goes to a landfill, and the concentrated waste stream produced by the system may be re-used on-site as animal feed or mixed with primary sludge. Widespread market adoption of this technology will make water reuse for food processors more economical and energy efficient compared to current leading technologies.

Keywords: wastewater treatment, high-starch wastewater streams, food processor, forward osmosis recycler, reverse osmosis, California Energy Commission

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Background

Inexpensive water reuse is a pain-point for food and beverage manufacturers, especially in water-stressed areas like Southern and Central California. Rising waste disposal costs and water sourcing expenses further impact food and beverage manufacturers that produce difficult-to-treat high-starch wastewater streams from their facilities. Processors are looking for solutions that will help offset costs and allow them to remain market competitive. Forward osmosis (FO) is a water separation process where water travels across a semipermeable membrane. Forward osmosis has unique advantages for food and beverage applications because it can operate reliably when processing challenging liquids that quickly clog or foul other types of membrane processes, such as reverse osmosis (RO) that are pressure driven. High starch waste represents a new frontier for membrane-only systems like the Porifera's Forward Osmosis (PFO) Recycler. Conventional membrane processes require multiple pretreatment steps and frequent cleaning to be able to operate reliably, resulting in an energy-intensive and expensive process. Comparatively, the PFO Recycler has many advantages over its competitors:

- It produces exceptionally clean water.
- It requires lower energy to operate (up to 50 percent less than a Membrane Bioreactor [MBR] at commercial scale).
- It requires a smaller footprint to operate.
- It is easier to scale the system size as no bioreactors are required.
- It has a wide pH operating range (2 to 11).
- No biological treatment is required.
- No brine disposal is needed.
- No waste produced goes to landfills.
- The concentrated waste stream produced by the system may be reused on-site as animal feed or mixed with primary sludge.

The PFO Recycler will make water reuse economical and energy efficient for food processors and others seeking to treat high starch wastewater. This technology will become increasingly valuable as the cost of water and waste disposal continue to rise.

Project Purpose and Approach

The purpose of this Project was to demonstrate the PFO Recycler system (optimized for high starch content) to reduce energy, chemicals, and maintenance required for reuse of hard-to-treat industrial wastewaters. The objectives of this Project were to:

- Complete design, optimization, and testing of a prototype PFO Recycler for starchy wastewaters.
- Install and test PFO Recycler systems for reuse of starchy wastewaters in both a lab environment and in representative commercial facility at a small scale.

- Assess the benefits of the PFO Recycler including lower energy, fewer chemicals, and less maintenance.
- Evaluate energy savings and increased water volumes for reuse.

Over a four-year period, a phase-based approach was developed to execute this Project, during which Porifera performed the following activities:

- Selected a suitable Project site (Frito Lay at Modesto, California) in collaboration with the Project Partner (Frito-Lay).
- Conducted lab-scale experiments to select a wastewater stream with high starch content.
- Tested multiple pre-treatment systems at the Project site.
- Designed, installed, optimized, and operated a pilot system to demonstrate system benefits, energy savings, and accelerate commercial adoption.
- Collected continuous and periodic sample data (which was sent to an independent laboratory for verification).
- Measured and verified energy by an independent third-party (CDM Smith).

Key Results

Water Quality Results and Projected Energy Savings

Despite high organics and solids loading in the wastewater treated (average COD>2500 mg/L), the PFO Recycler system produced clean water. Lab results from Eurofins indicated excellent performance by the PFO Recycler system in treating and removing the following parameters of interest:

Metric	Concentration in Permeate (mg/L)	Removal
Total dissolved solids (TDS)	16	99%
Total soluble solids (TSS)	Non-detect	100%
Chemical oxygen demand (COD)	6	99.8%
Biological oxygen demand (BOD)	4.7	99.1%
Hardness	Non-detect	100%
Nitrogen	0.31	99.7%
Oil and grease	Non-detect	100%
Environmental Protection Agency (EPA) contaminants	Below maximum contaminant limit	High
EPA metals	Below maximum contaminant limit	High

The energy use at commercial scale was determined to be 50 percent less than the energy use of commercial MBR+RO systems, with the operating expenses (OPEX) reduced by 10 percent.

Metric	PFO Recycler System	Current Market Leading Technology
	Commercial System Projections	Membrane Bioreactor (MBR) + RO with Ancillary Equipment
Total energy consumption [kWh/1,000 gal permeate]	14.5	29.07

The "Total Energy Consumption" denotes how many kilowatt-hours (kWh) of electrical energy are required to produce 1,000 gallons of clean water.

Key Learnings and Future Development Opportunities

System efficiency and power consumption can be improved up to 50 percent in commercial-scale systems by using energy efficient drives and pumps and improving prefiltration.

Future technology explorations include testing prefiltration via clarifiers, hydro cyclones, or microfiltration systems. Porifera has previously used microfiltration to achieve continuous FO-RO operation with high flux (six LMH [liters per square meter per hour]) and high recovery (up to 90 percent) without the need for frequent clean-in-place (CIP) systems. A combination of these technologies is currently being explored for a large commercial scale system to treat paper pulp fibers in wastewater.

Benefits to California's Clean Energy Goals, with Intangible Ratepayer Benefits

As PFO technology gains momentum, the qualitative and intangible benefits to California ratepayers will grow correspondingly:

- Decreased water costs compared to more traditional sources (such as surface water) in drought prone regions for which costs continue to rise.
- Providing unique solutions for water reuse that will increase water availability during droughts while increasing safety of the water supply.
- Decreased pumping between Northern California and Southern California during non-drought years allowing more of the water from the State Water Project to be used for environmental restoration, agriculture, or hybrid cooling of power plants.
- High quality industrial reuse and potable reuse with softer and less salty water than standard non-potable recycled water (soft water improves energy efficiency of cooling towers, boilers, refrigeration, and other industrial and commercial equipment).
- Increased hydroelectric power during drought years from the state and federal hydroelectric systems if local municipalities can discharge reuse water directly into, or decrease diversions from, reservoirs that generate electricity.

Knowledge Transfer and Next Steps

The intended use of the Project results was to demonstrate, through data collection and analysis, the advantages of the Recycler technology. Porifera produced a detailed technoeconomic analysis with data from the demonstration and shared the analysis with the customer.

Porifera performed both passive and active information sharing activities. Passive sharing activities include development of a business case study, marketing materials and additional relevant materials. Active sharing activities included hosting booths at tradeshows and exhibitions, in addition to oral presentations given both in person and virtually.

Porifera plans to continue sharing the benefits of its Recycler technology through both general marketing collateral as well as targeted information for food and beverage processors with wastewater processing needs. Porifera maintains its presence at, and contributes to, food and beverage expos and conferences. Porifera’s website will be continuously updated with new case studies and products obtained with the PFO Recycler technology.

Combined with an appropriate prefiltration system, Porifera can scale-up the Recycler system for commercial applications through its modular design by adding more membrane area and increasing the number of stages needed to treat larger quantities of wastewater. Reduced solids on the FO elements will allow the RO system to operate at a lower pressure, while reducing operating expenditure costs. Future technology explorations include testing prefiltration via clarifiers, hydro cyclones, or microfiltration systems. A combination of these technologies is currently being explored for a large commercial scale system to treat paper pulp fibers in wastewater.

CHAPTER 1: Introduction

Porifera Company Overview

Porifera Inc. is a California-based company that manufactures proprietary forward osmosis (FO) membranes and provides process solutions to a variety of industries. Porifera's innovative FO solutions enable industries to efficiently remove water and retain only the most valuable components of their products. This unique technology facilitates the minimization of water waste, improvements to water reuse, and more efficient processing solutions to create better products using less energy.

Porifera operates a 25,000 square-foot facility at its San Leandro, California headquarters. The facility contains administrative offices, engineering workspace, loading docks, a membrane characterization laboratory, and a food and beverage laboratory. The facility is equipped with several chemical hoods and other chemistry instrumentation.

Porifera operates another 12,500 square-foot manufacturing facility, also in San Leandro, California. This facility contains semi-automated equipment for assembly of PFO elements and modules as well as quality assurance testing equipment.

Porifera Technology Overview

Introduction to Forward Osmosis

Forward osmosis is a water separation process where water travels across a semipermeable membrane. Water travels from an aqueous solution with lower concentration of solutes (feed solution) to an aqueous solution of higher concentration of solutes by osmosis. Forward osmosis has unique advantages for food and beverage applications because it can operate reliably when processing challenging liquids that quickly clog or foul other types of membrane processes, such as reverse osmosis (RO) that are pressure driven.

Porifera Forward Osmosis Recycler

Porifera's Recycler combines the company's proprietary forward osmosis (PFO) and modified RO technology to achieve greater product concentrations than conventional RO technologies can achieve on their own.

First, the PFO Recycler concentrates wastewater and produces a clean water stream by feeding wastewater on one side of the PFO membrane and passing salt water by the other side. The osmotic pressure of the salt water is calibrated to be greater than the osmotic pressure of the wastewater. This difference in "osmotic potential," causes pure water to be pulled through the membrane and into the salt stream, causing the wastewater to dewater and concentrate with low energy input.

The single step RO stage then dewaters and re-concentrates the diluted salt stream, allowing it to cycle back for continuous reuse. An optional permeate polishing step can be used for this application to achieve the highest possible water quality. Pure product water is created for on-site reuse while the concentrated reject stream can be either disposed or re-used as a product at the discretion of the Project partner and/or client.

Porifera's PFO Recycler innovations are unique compared to other FO technologies. The PFO Recycler can:

- Operate reliably on challenging liquids with high solids, pulps, free and emulsified oils and greases, high chemical oxygen demand (COD), high biological oxygen demand (BOD). Porifera is the only FO provider of spacer-less elements suited to these applications.
- Achieve higher membrane flux, rejection, and efficiencies than competing FO technologies using the same draw solution chemistry.
- Operate at high rejection and high efficiencies using a draw solution (that is table salt) that is easily recyclable using RO. Competing FO technologies require toxic draw solutions or allow too much leakage of the draw salt into the product.
- Operate at temperatures up to 60°C. Standard FO & RO membranes cannot exceed 45 °C, which negates potential energy savings in high temperature reuse applications (that is, boiler feed, sterilization, or when reheating is required).
- Operate at a wide range of pH (2 to 11), expanding the applicability of FO-based solutions, which in the past could not operate at low pH levels.

The PFO Recycler has multiple advantages over other advanced treatment technologies as described in Table 1.

Table 1: PFO Recycler and Competing Technologies for Hard-to-Treat Wastewater

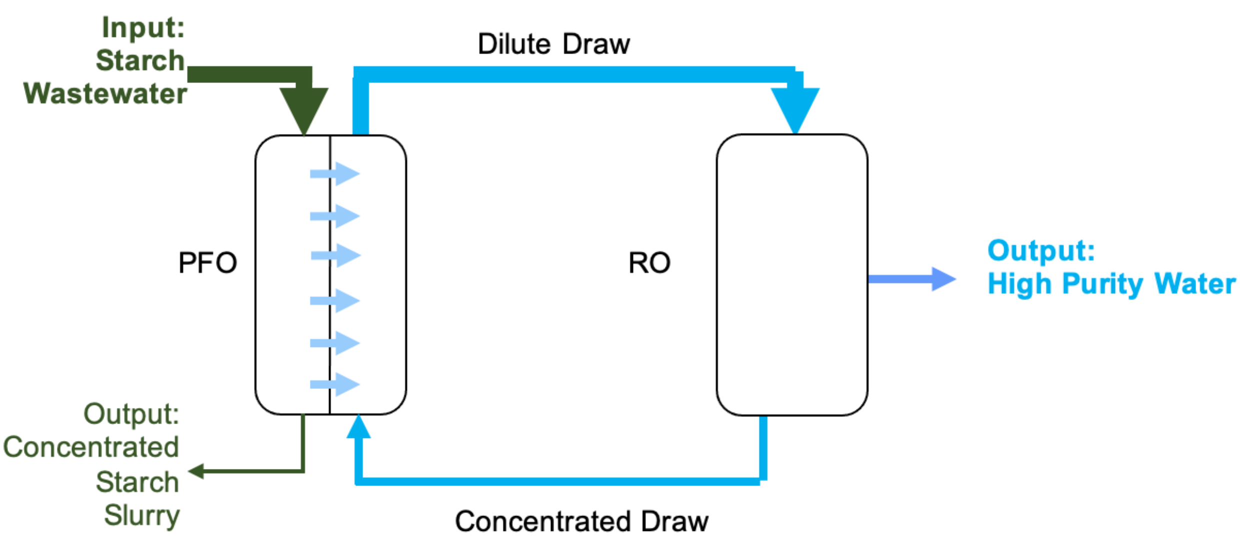
Technology	Reliability	Water Purity for Reuse	Limits & Notes
Pretreatment +Nanofiltration	Not reliable	Poor. Small molecules such as sugars pass through the membrane so water will be unfit for reuse.	COD: <10 mg/L Oils and grease: <0.1 mg/L Temp: <45°C Not reliable when starch and sugars are present
Ultrafiltration + RO	Poor, frequent cleanings	Fair. RO water is usually extremely high quality. However, the COD may be over 10 mg/L, exceeding the reuse target for water used in food processing equipment.	COD: <60 mg/L Oils and grease: <2.0 mg/L Temp: <45°C Not reliable when starch and sugars are present.
Membrane Bioreactor + RO	Moderate, high maintenance and semi-frequent cleanings	High. Biological step reduces BOD to a more manageable concentration for RO than UF. Additional treatment steps required for reliable reuse.	Better than UF+RO for high BOD and starchy wastes; four additional treatment steps needed

Technology	Reliability	Water Purity for Reuse	Limits & Notes
			at needed to reuse water
Evaporators + distillers	Poor to moderate	Poor. Volatile Organic Compounds (VOCs) remain in the condensate.	Expensive, poor solution for high starch, BOD, and COD wastes
Porifera's PFO Recycler	High, target is unmanned operation with infrequent cleanings	High. Two barriers for all contaminants. UVAOP not likely required.	COD: >100,000 mg/L Oils and grease: >50 mg/L Temp: <80°C for PFO step

Source: Porifera Inc.

Our PFO Recycler is a versatile water treatment system that can handle a wide variety of challenging high starch BOD/COD wastewater feed streams containing high levels of suspended solids (Figure 1). Our PFO Recycler is comprised of PFO Modules optimized for this challenging application with a customized RO draw regeneration system. The PFO Module is our platform technology that can treat a wide variety of challenging feed streams across many different industries.

Figure 1. Process Flow Diagram of PFO Recycler



Process flow diagram of PFO Recycler demonstrating input and output streams including wastewater, dilute, and concentrated draw, and high-purity water.

Credit: Porifera Inc.

Project Goals and Objectives

The goal of this Project was to:

- Demonstrate the PFO Recycler technology for reuse of starchy industrial wastewaters.

The objectives of this Project were to:

- Install and operate a pilot PFO Recycler for reuse of starchy wastewaters in both a lab environment and in representative commercial facility at a small scale.
- Demonstrate the benefits of the PFO Recycler including low maintenance, chemical usage, and less energy.
- Demonstrate energy savings and increased water volumes for on-site reuse.

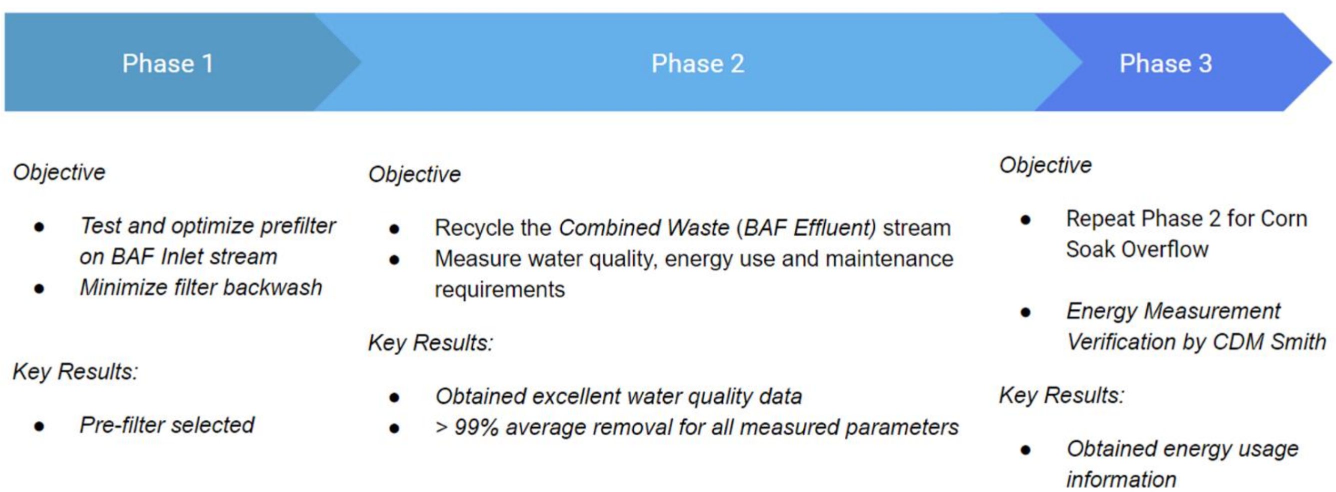
Project Timeline

To demonstrate the benefits of Porifera's technology, a phase-based approach was developed to install and operate a pilot PFO Recycler system for a California-based food and beverage processor. The first step included wastewater evaluation, process optimization, site preparation, pilot system design, manufacture, and testing. The second step included transportation, on-site installation, start-up, and optimization of the pilot system. The PFO Recycler ran at Frito-Lay's Modesto location for the length of time necessary to collect key performance data and measure energy savings. After piloting, the system was decommissioned from the production site.

Project Schedule

The Project activities occurred over a four-year period as shown in the Project timeline in Figure 2.

Figure 2: Project Timeline



Objectives and Key Results for Three Project Phases

Source: Porifera

Project Team

The Project team consisted of key employees of both Porifera and its Project partner, as listed below:

- Porifera Inc. –Olgica Bakajin, Charlie Benton, James Coyle, Erik Desormeaux, Antony Freggiaro, Corey Gonzalves, Martin Ingalls, Kirk Jensen, Chris Keith, Jennifer Klare, James Lalikos, Gustavo Pastre, Ravindra Revanur, Iljuhn Roh, and Nick Tangri.
- Frito-Lay Inc. – Mary Gomez, Jimmy Yu, Arun Sathyagal, Citlalli Pina, Sarai Nixon, Kristina Buddenhagen, Joe Novak

Location

The Project was executed at Porifera Inc. in San Leandro and in Frito-Lay Inc. facility in Modesto, California, where the PFO Recycler was installed and operated. Both locations are shown in Figure 3.

Figure 3: Project Locations: Porifera Inc. (a) and Frito-Lay Inc., Modesto (b)

Source: Google Maps

Equipment and Materials

The equipment and materials used for testing were different for each phase of the Project and are summarized below. The main components needed for Project execution were:

- PFO laboratory testing system
- Pilot-scale PFO Recycler system
- Feed solution (starch wastewater)
- Draw solution (sodium chloride [NaCl] solution)
- Disinfection and cleaning chemicals (caustic cleaner, Peracetic Acid [PAA], sodium metabisulfite)
- Sample containers suitable for storage and quality testing

The test equipment was designed, fabricated, and operated by Porifera. The feed solution, a combined process waste stream, was provided by the Project partner Frito-Lay in Modesto, and the draw solution and cleaning chemicals were provided by Porifera.

CHAPTER 2: Project Approach

Analysis and Prototype Design

The first step in the Project was to analyze and design prototype that will evaluate using PFO Recycler technology to reuse water and save energy at a Frito-Lay plant in California.

Site Analysis and Selection

Frito-Lay has three manufacturing facility locations in California: Modesto, Rancho Cucamonga, and Bakersfield. Porifera collaborated with Frito-Lay's corporate sustainability group in Texas and the global PepsiCo sustainability group in New York to evaluate Porifera Recycler technology for the three sites. This included conference calls and presentations to educate them on typical performance and benefits of the technology as well as the discuss challenges at each site.

Frito-Lay and PepsiCo corporate staff selected the Modesto site for three reasons:

1. This site has both corn chip and potato chip waste streams and thus is expected to have wastewater representative of the other two sites.
2. This site has a significant need for water security and already has some recycled water infrastructure.
3. This site is in the process of an expansion, which will further increase its need for additional water recycling.

Porifera worked with Frito-Lay corporate and site staff to complete an agreement for the work on-site. A non-disclosure agreement was negotiated and executed. Porifera staff also visited the site and submitted a plan and schedule for pilot testing and had multiple planning calls to discuss how to execute the Project and to discuss details at the proposed location on the site.

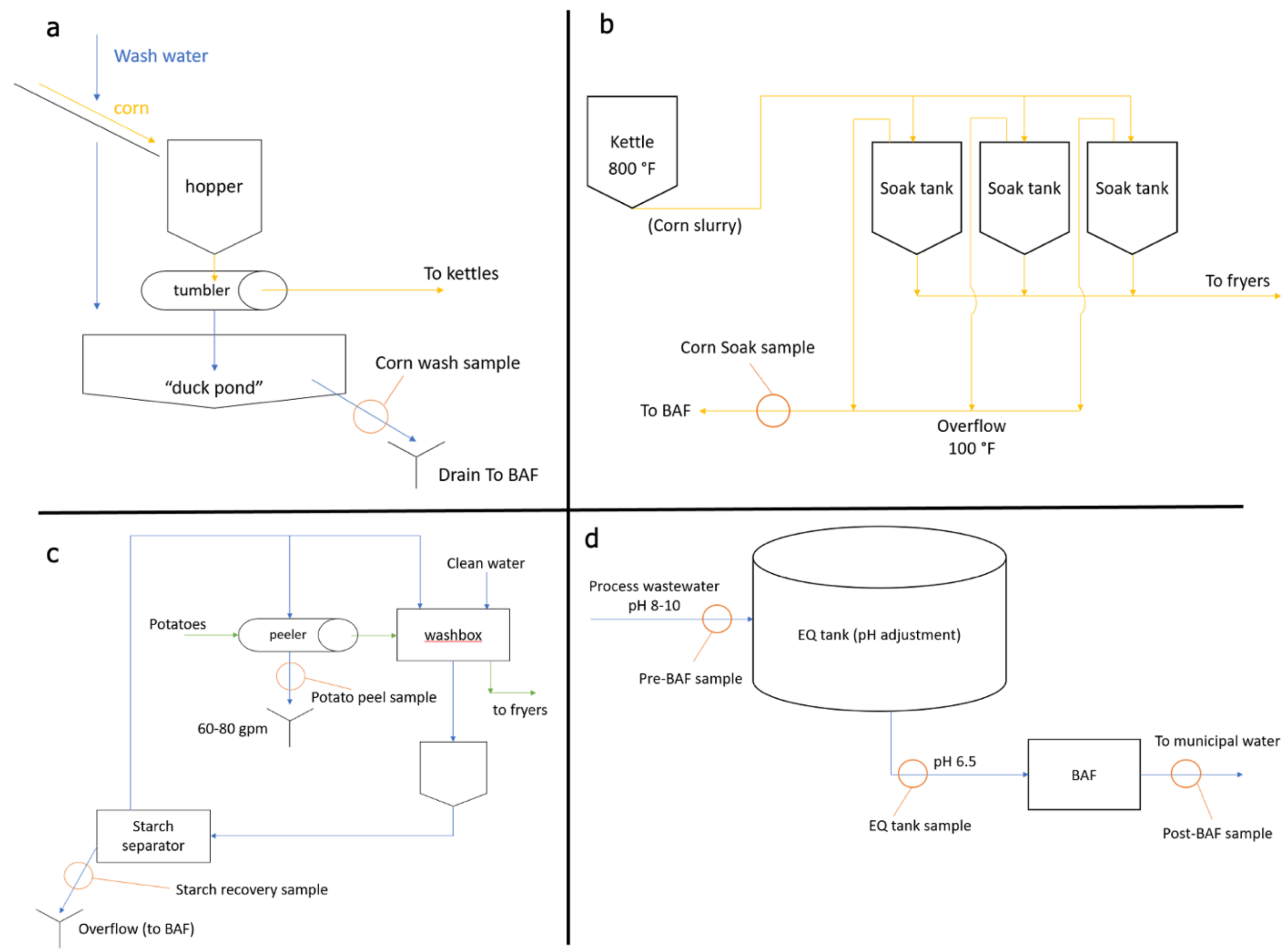
Wastewater Analysis and Selection of Waste Streams for Pilot Testing

The Modesto location processes both corn and potato products, which allowed for a larger sample pool to be analyzed. Samples were taken from both potato and corn lines, as well as the combined process wastewater streams. The sample locations were described as follows:

1. Corn soak overflow
2. Corn rinse water
3. Potato peeler wash water
4. Starch recovery effluent
5. Pre-equalization (EQ) and bulk air flotation (BAF)
6. EQ tank, and
7. Post-BAF

Figure 4 illustrates where each sample was collected within the overall process including the corn soak process, the corn cook process, potato peeling and starch recovery process and the final combined wastewater treatment and discharge process, which includes pH adjustment in an equalization tank and a BAF treatment system that adds polymer and air to float out some particles prior to sewer discharge.

Figure 4: Sample Collection Sites: Collection Vessel for the Used Corn Wash Water (a), Overflow of the Tanks Where the Corn is Soaked in Lime (b), Used Potato Wash Water Stream and the Overflow from the Starch Recovery Process (c), Three Samples of Total Plant Wastewater (d)

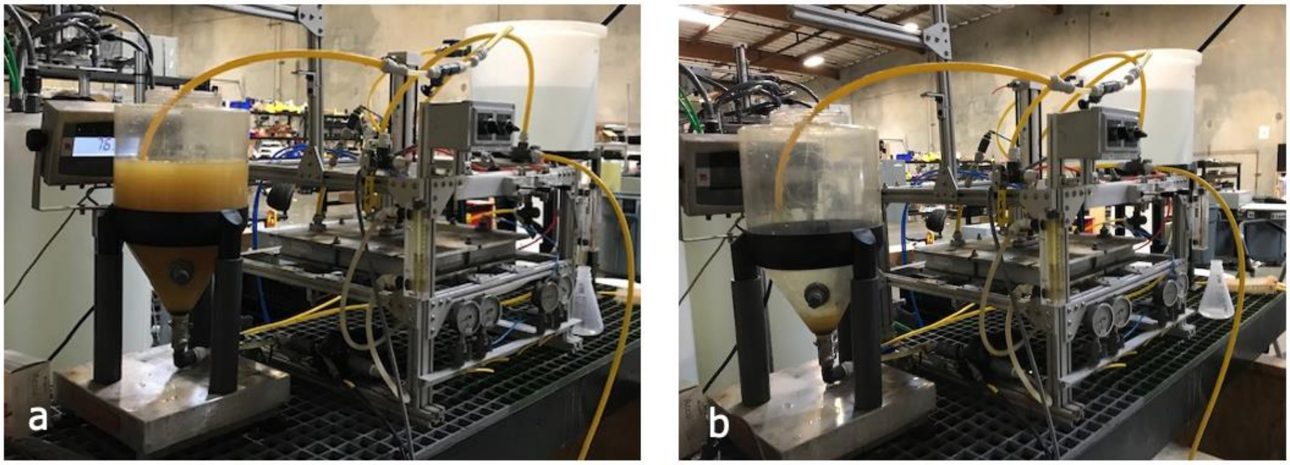


Schematic diagram of four collection sites

Credit: Porifera Inc.

Each sample was analyzed both by a Porifera scientist and a third-party laboratory. The in-house tests were conducted to determine a viable FO flux and recovery for each sample, as well as which samples were likely to be more challenging in terms of clogging or fouling the FO membrane. Using the testing apparatus shown below, concentration factors of 10 times were achieved with each sample without damaging the membrane, indicating that there were no major membrane incompatibilities. Pictures of the in-house setup are presented in Figure 5.

Figure 5: PFO Testing Setup with Prototype Element: Initial (a) and Final (b)



Credit: Porifera Inc.

Each test used an initial draw of 4.5 weight (wt.) percent sodium chloride (NaCl). The results of the testing, along with notes about the feasibility of each stream are shown in Table 2.

Table 2: Summary of In-House Testing

SAMPLE	INITIAL FEED SALINITY (mS/cm)	FINAL FEED SALINITY (mS/cm)	INITIAL DRAW SALINITY (mS/cm)	FINAL DRAW SALINITY (mS/cm)	PILOT FEASIBILTY CONSIDERATIONS Notes
Corn Soak	3.7	20.5	70	57.2	+ Good location outside + Heat recovery for boiler reuse + Starch recovery? Can reduce sewer bill. - Intermittent flow
Corn Rise	1.6	15.54	70	52.7	+ Easiest to treat. - Impractical location
Potato Peal	1.3	13.9	71	54.2	- Goes septic quickly - Impractical location
Starch Recovery	1.6	10.61	71	53.0	+ Many benefits to site - Goes septic quickly - Challenging location
Before EQ+BAF	1.2	12.9	70.5	53.2	+ Good location +high pH, septic more slowly - Highly variable scaling potential
EQ Tank	1.1	13.5	70.2	55	+ Good location + Less variable - Neutral pH may go septic quickly

SAMPLE	INITIAL FEED SALINITY (mS/cm)	FINAL FEED SALINITY (mS/cm)	INITIAL DRAW SALINITY (mS/cm)	FINAL DRAW SALINITY (mS/cm)	PILOT FEASIBILTY CONSIDERATIONS Notes
After BAF	1.8	13.6	70	52.7	+ Good location + Reduced solids loading. - Polymer occasionally overdosed

Source: Porifera Inc.

There were several practical considerations for each sample that were important in terms of sample selection for pilot testing. These were included in the last column of Table 2, titled "Pilot Feasibility Considerations." To determine each sample's composition, small volumes were sent to McCampbell Analytical, Inc. in Pittsburgh, California. Their report provided COD, hardness, total soluble solids (TSS), and ionic composition of each sample. The data indicated that there will be times with the combined wastewater that scaling potential will be a concern for the combined water quality.

Recommendations from Water Testing Analysis

The following notes and recommendations came out of the analysis:

- **Reuse purpose:** Frito-Lay wanted to evaluate reusing water for boiler feed, corn soak heating, and other reuses.
- **Stream selection:** Frito-Lay and Porifera agreed that the corn soak and final combined effluent would be the best candidates for pilot testing in terms of benefits for Frito-Lay, fit for the technology, and practical considerations (location and space).
- **Alternative stream:** The starch recovery stream was identified as a third possible target stream by PepsiCo global staff; however, due to the location of this waste stream, there will be many practical challenges to execute pilot testing on this stream.
- **Pre-treatment:** A pre-strainer would aid in removal of larger starch particles and anti-scalant chemical addition may be necessary for some streams.
- **FO configuration**: spacer-less elements in a recirculation system were recommended to reduce cleaning intervals.

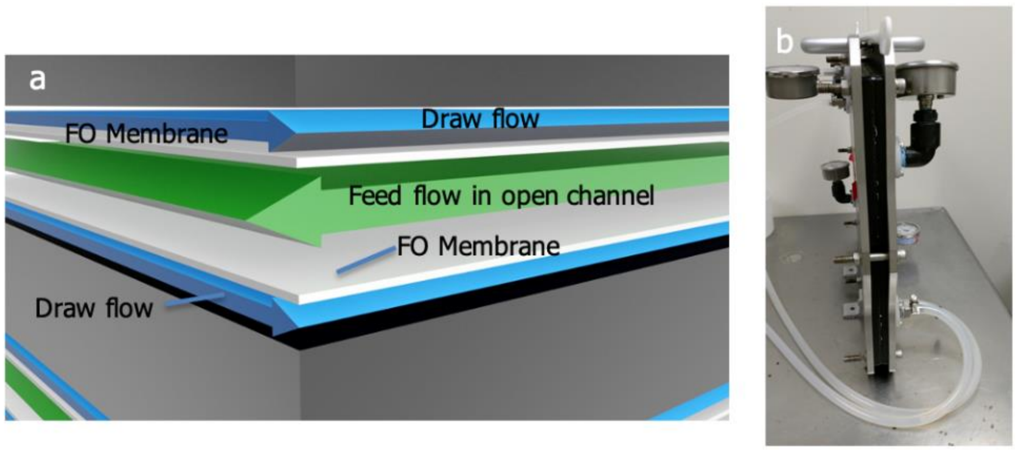
Process Stream Selection for Pilot Testing

Once water quality, test results, and site feasibility considerations were assessed, Porifera and Frito-Lay staff collaborated to select the corn soak and equalized final combined waste stream (before the BAF) as the two target streams for pilot testing. The system was then designed to treat those streams. The starch recovery stream was identified as a third possible target stream by PepsiCo global staff. However, due to the location of this waste stream, there would be many practical challenges to execute pilot testing on this stream.

Prototype Design

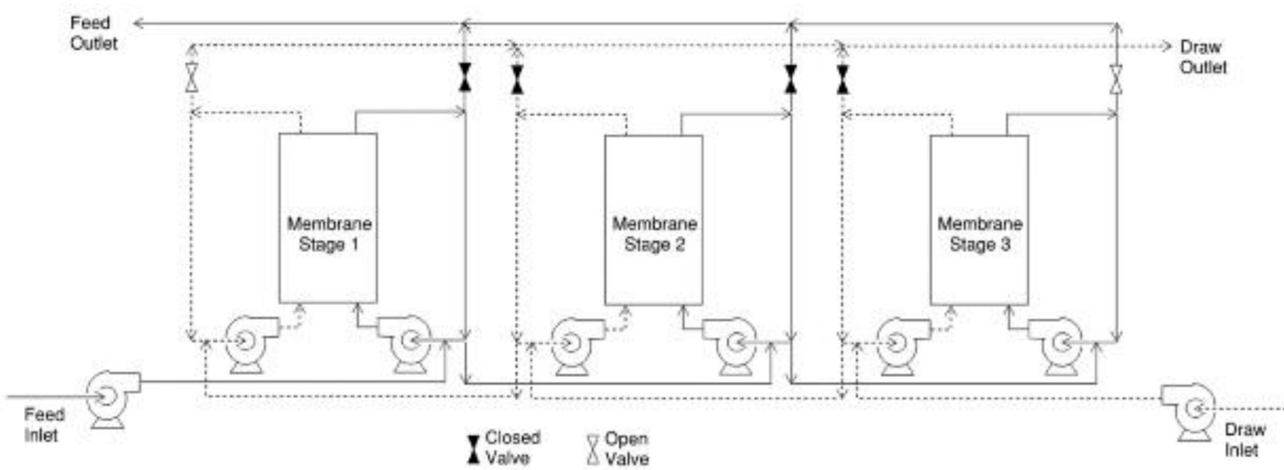
Porifera's spacer-less PFO elements were critical for successful treatment of these starchy wastewaters. The PFO Recycler was designed with the PFO elements installed in a multi-stage system that provided continuous high surface velocity across the membrane surface. This high velocity reduced the impacts of starchy solids by keeping the solids suspended and well mixed. Removing the spacer provided an open channel for flow so that the feed would not stick to the spacer material and clog the flow paths. Figure 6 shows a picture of the FO spacer-less element used for testing and Figure 7 shows a graphic of the multi-stage recirculation type system design.

Figure 6: PFO Spacer-less Element Flow Path Illustration (a) and Test Unit (b)



Credit: Porifera Inc.

Figure 7: FO Multistage Recirculation Approach



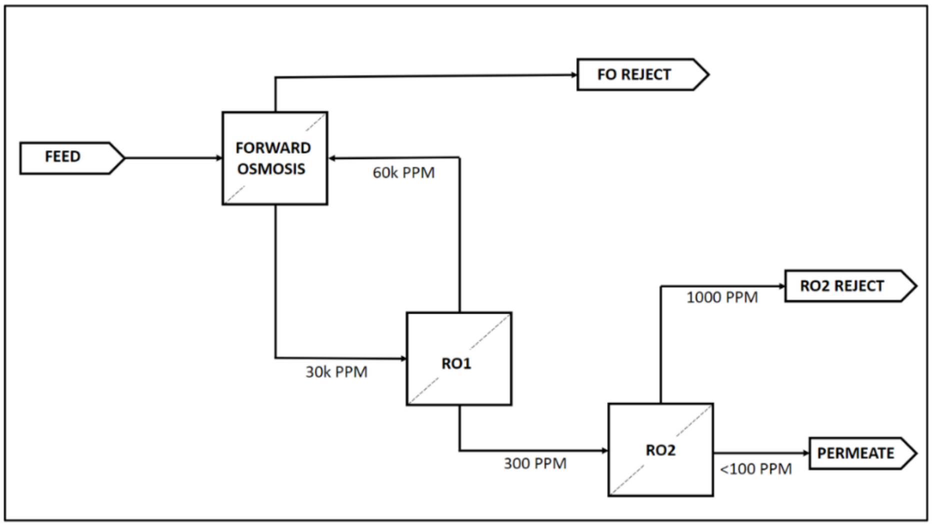
Schematic diagram of the Recycler system's recirculation approach

Credit: Porifera Inc.

System Related Design

The system design consisted of two main components: the FO front end and the RO back end, along with some additional support equipment. The initial design was based on 85 percent FO recovery, a single stage of RO at 50 percent recovery, and 10 gallons per minute of permeate at less than 500 TDS. Based on later discussions with plant staff, the target permeate quality was changed to less than 200 TDS. This change necessitated the addition of a second stage of RO, slightly reducing the total permeate production rate while greatly increasing its purity. The latest flow rate and concentration values are summarized in the process flow diagram (Figure 8). Concentrations represent NaCl content in the draw solution in parts per million (PPM).

Figure 8: Process Flow Diagram

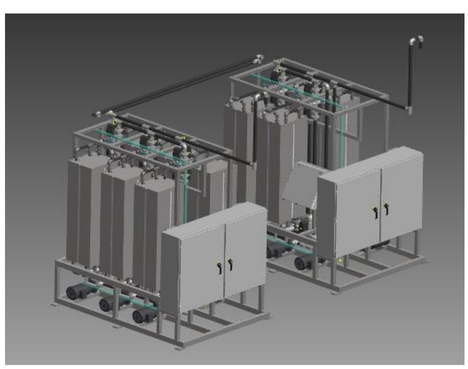


Process flow diagram of the overall system

Credit: Porifera Inc.

For the FO front end, 90 total elements were divided into five stages, with each stage containing two stacks of 9 elements each. Each stage had a pump continually recirculating fluid within the stage, both for the feed and draw solution. The recirculation allowed for high fluid velocities through the large channels within the elements, as well as greater pressure control. This led to higher flux without significant head loss. A complete three-dimensional (3D) rendering of the FO system is presented in Figure 9. The system was provided with DOW seawater RO elements (4040).

Figure 9: 3D Model of the FO System



3D Model of the FO system showing PFO-100 element stacks, recirculation pumps, electrical components, and plumbing.

Credit: Porifera Inc.

In addition to the main FO and RO systems, a cleaning system was designed to control biological fouling and mineral scaling. The clean-in-place (CIP) system consisted of a tank and pumps and was designed to mix and introduce chemicals to the system in the event of fouling or unexpected shutdown.

Pilot Implementation Overview

Pre-filtration Study

Prior to installing the Recycler system, Porifera conducted a test to select a pre-filtration system:

- Porifera installed a small-scale testing apparatus on-site. It was fitted with a prefiltration system containing a polymeric disc filter with an automatic backflush routine. The combined waste stream was used for testing.
- Testing began with 40-micrometer (μm) filter discs. High levels of solid fouling were observed, and backflushes were ineffective at removing foulants.
- The 40 μm filter discs were replaced with 130 μm discs. However, fouling was not reduced, and backflushes were ineffective. It was determined that this system was not a viable option for pre-treatment.
- It was replaced by an alternate prefiltration system that was comprised of a stainless-steel screen filter and a motor-driven cleaning brush. The rotating brush continuously augured any embedded solids downwards (where they were expelled during a purge routine).
- The new system was operated continuously without major fouling or excessive pressure drop.

During the pilot, it was observed that although the second pre-filtration system did not foul, it allowed a large quantity of solids to be pushed through its filter screen, resulting in fouled FO elements.

Pilot Implementation

After the pre-treatment study, the pilot system was installed on-site (Figure 10) and started on June 11, 2021. The feed was initially supplied from an existing overflow tank at the inlet to a BAF system. This water was pumped from the tank through the pre-filtration unit to the Recycler system. During initial operation, frequent cleanings were required (more than two per week); there were clear indicators that the starchy suspended solids had bypassed the pre-filter and fouled the FO membrane, in turn leading to reduced system performance.

When it became apparent, in August 2021, that the pre-BAF stream was not conducive to the equipment set-up, the feed source was moved to the BAF effluent, which has a lower solids content. The water from this stream was accessed from an open steel basin at the outlet of the BAF. With the reduced solids loading, the system was able to operate more reliably, although regular CIPs were still needed (once per week). However, the already damaged membrane needed to be replaced. To mitigate risk and reduce potential for waste, in October

2021, the amount of membrane on the system was reduced from 630 square meters (m^2) to 126 m^2.

After operating the machine using the BAF effluent stream long enough to collect a significant set of data, Porifera and Frito-Lay agreed to run a short test using the corn soak stream. Because this water source was intermittent and not easily accessible, continuous testing was not possible. Rather, 275-gallon totes were filled from a tap on a pipe inside the production facility and moved by forklift to the PFO system. In June 2022, over the course of two days of operating, the PFO system processed over 500 gallons of the corn soak water with no observable issues.

Figure 10: PFO Recycler System at Frito-Lay, Modesto

Credit: Porifera Inc.

Clean-In-Place Procedure

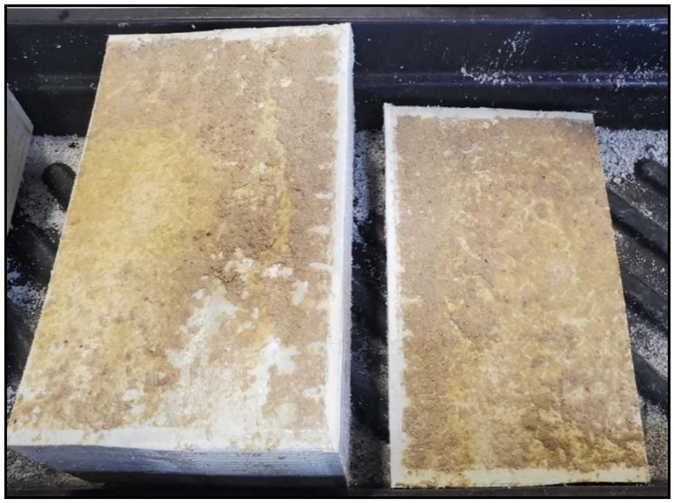
To remove foulants, a solution of sodium hydroxide with a chelant additive (pH 11 to 11.5) was pumped into the system on both the feed and draw sides of the membrane. The recirculation pumps at each stage pushed the cleaning solution through the membrane flow channels at high surface velocities to provide the best cleaning possible. Generally, the cleaning duration is dependent on the level of fouling, and typical durations fall in the range of 40 to 90 minutes.

In the event of a long-term shutdown (where on-site maintenance may be required for restart), the PFO membrane modules were filled with a pickling (antimicrobial) solution, sodium metabisulfite, of two percent by weight. This prevented biological growth on the membrane until an operator could service and clean the system.

Membrane Cleaning Study

During the pilot, fouled FO elements were brought back to Porifera's lab, where cleaning studies were performed. By performing flux tests after subjecting the elements to various cleaning procedures, it was determined that hot water (45 °C) mixed with CIP chemicals was effective in removing large quantities of foulant. On-site hot water lines were used thereafter to mix chemicals with the CIP system. Figure 11 shows the accumulation of starch solids on an autopsied FO membrane element.

Figure 11: Autopsy of a Fouled FO Element



Cut element showing fouling (accumulation of starch solids)

Credit: Porifera Inc.

CHAPTER 3: Results

Measurements Performed

Throughout the pilot, the Porifera's team collected multiple data points to monitor and measure the PFO Recycler's capability to treat starch-laden wastewater. Data was collected via:

- Industry standard measurement equipment from IFM Efector, integrated into the PFO Recycler system.
    - Flowmeters
    - Pressure Sensors
    - Conductivity Meters
    - Temperature Sensors
- Sample Collection Kits
    - Sent via PepsiCo to an independent laboratory (Eurofins) for analysis and verification.

Continuous Data Collection

During machine operation, the following parameters were continuously collected by the PFO Recycler system:

- Flowrate: feed, permeate, and reject streams
- Conductivity: feed, permeate, and draw streams
- Temperature: feed, permeate, and draw streams
- Pressure: RO pressure

Periodic Sample Grabs

During machine operation, the following parameters were periodically collected by the PepsiCo/Porifera team (via sample kits) and sent to Eurofins for analysis and verification:

- Total Dissolved Solids (TDS)
- Total Suspended Solids (TSS)
- Chemical Oxygen Demand (COD)
- Hardness
- EPA Metals Analysis and EPA Full Suite
- Acrylamide
- Ammonia Nitrogen
- Calcium Total ICAP
- Kjeldahl Nitrogen

- Magnesium Total ICAP
- Oil and Grease
- Orthophosphate as phosphor (P)
- Orthophosphate as PO_4
- Sulfate
- Total Hardness as $CaCO_3$ by ICP
- Total Organic Carbon
- Total phosphorus as P
- Total phosphorus as PO_4
- Biochemical Oxygen Demand

Later, it was determined that the following metrics would be areas of focus for this Project: TDS, TSS, COD, Hardness, EPA Metals Analysis, and EPA Full Suite

Operational Performance and Results

Periodic Sample Grab Results

Lab results from Eurofins indicated excellent performance by the PFO Recycler system in treating and removing the following parameters of interest* (Table 3). Figure 12 shows the permeate quality in comparison to the raw wastewater.

Table 3: Periodic Sample Grab Result Summary

Metric	Concentration in Permeate (mg/L)	Removal
TDS	16	99%
TSS	Non-detect	100%
COD	6	99.8%
BOD	4.7	99.1%
Hardness	Non-detect	100%
Nitrogen	0.31	99.7%
Oil and grease	Non-detect	100%
EPA contaminants	Below maximum contaminant limit	High
EPA metals	Below maximum contaminant limit	High

Credit: Porifera Inc.

** After an initial review of Microbial (HPC, Total Coliforms) test data indicating excellent performance by the Recycler in treating and removing coliforms (99.999 percent), further testing was paused.*

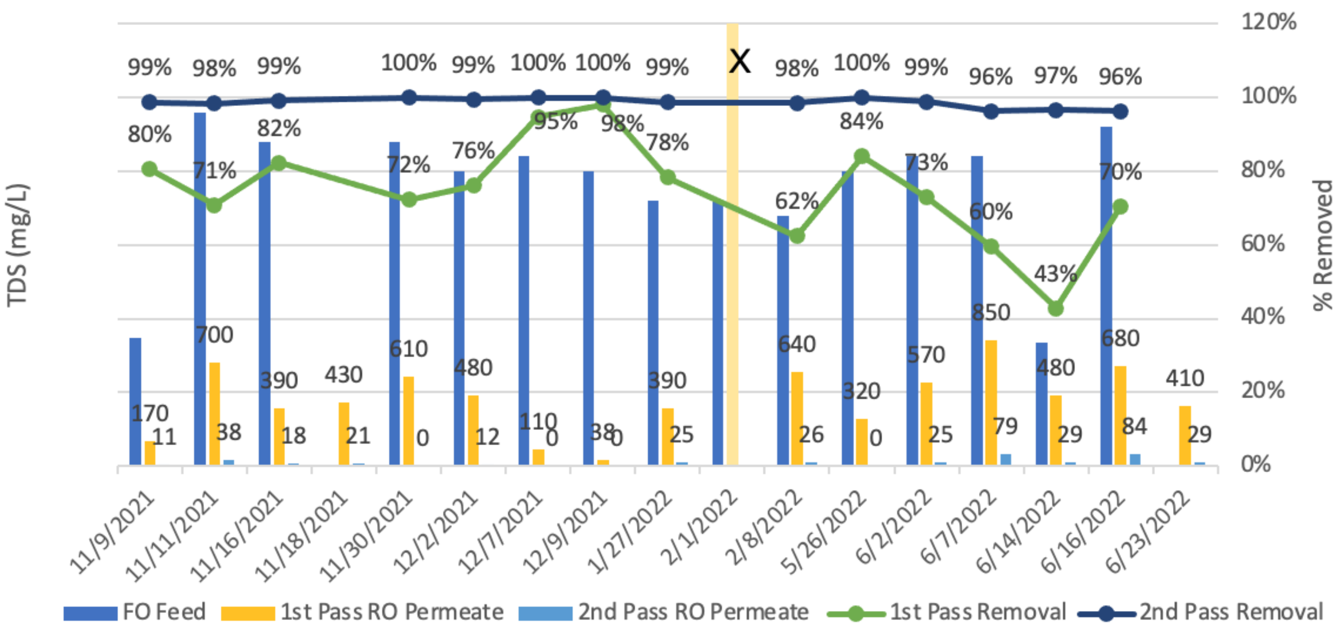
Figure 12: Raw Wastewater (left) and PFO Recycler Permeate (Right)

Credit: Porifera Inc.

Total Dissolved Solids

- On average, the Recycler system removed 99 percent of TDS present in the feed wastewater through its dual RO "polishing" stage (as demonstrated in Figure 13).

Figure 13: TDS Removal Performance



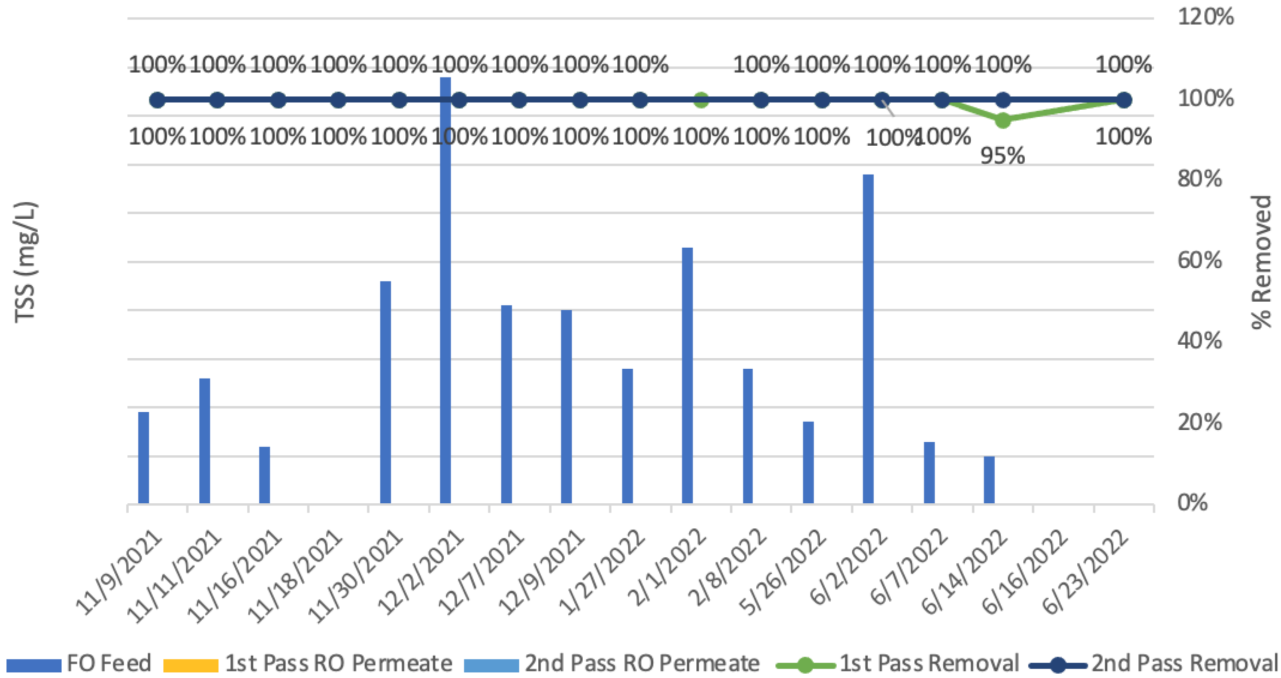
Feed water quality values (mg/L) are confidential. 0 represents values below the detectable limit.
X - Samples collected on 2/1/2022 were subject to contamination.

Credit: Porifera Inc.

Total Suspended Solids

- On average, the Recycler system removed 100 percent of TSS present in the feed wastewater in combination with a variety of prefiltration systems (as demonstrated in Figure 14).

Figure 14: TSS Removal Performance



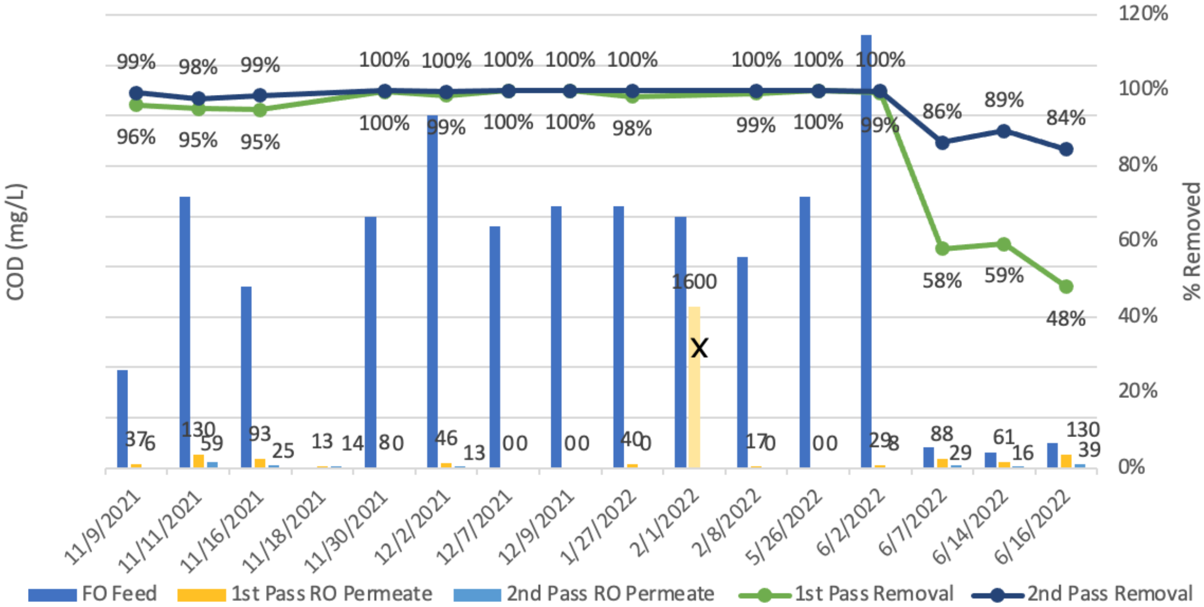
Feed water quality values (mg/L) are confidential. 0 represents values below the detectable limit.

Credit: Porifera Inc.

Chemical Oxygen Demand

- Between 11/9/2021 and 6/2/2022, on average, the Recycler system removed over 99.8 percent of COD present in the feed wastewater across multiple pre-filtration systems, resulting in an average COD of 6 mg/L in the permeate stream.
- As demonstrated in Figure 15, FO feed samples collected between 6/7 to 6/16 indicate a change in water quality (average COD dropped by 10 times). Although the COD removal percentage indicates a slight dip in performance, the average permeate water quality remains unchanged.

Figure 15: COD Removal Performance



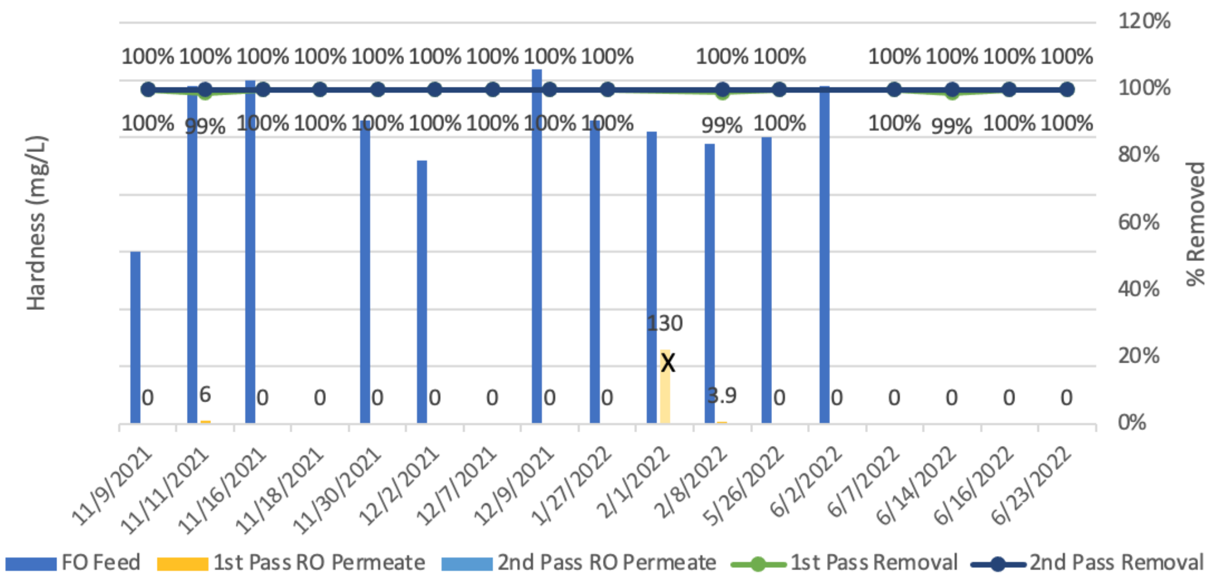
Feed water quality values (mg/L) are confidential. 0 represents values below the detectable limit. X – Samples collected on 2/1/2022 were subject to contamination.

Credit: Porifera Inc.

Hardness

- On average, the FO-RO system removed 99.7 percent of hardness present in the feed wastewater through its dual RO polishing stage (as demonstrated in Figure 16).

Figure 16: Hardness Removal Performance



Feed water quality values (mg/L) are confidential. 0 represents values below the detectable limit. X - Samples collected on 2/1/2022 were subject to contamination.

Credit: Porifera Inc.

EPA Metals Analysis

Sample grab results indicate excellent performance in treating and removing metals from the feed water. All values of the polished permeate were below the Maximum Contamination Limit (MCL) provided by Frito-Lay and are shown Table 4 below.

Table 4: Results from EPA Metals Analysis Sample Grab

Analytes	Unit	Max Contamination Limit (MCL)	Raw Wastewater	Recycler Permeate
Aluminum Total ICAP/MS	ug/L	1000	Confidential	ND
Antimony Total ICAP/MS	ug/L	6		ND
Arsenic Total ICAP/MS	ug/L	10		ND
Barium dissolved ICAP/MS	ug/L			ND
Barium Total ICAP/MS	ug/L	1000		ND
Beryllium Total ICAP/MS	ug/L	4		ND
Boron Total ICAP	mg/L			ND
Cadmium Total ICAP/MS	ug/L	5		ND
Calcium Total ICAP	mg/L			ND
Chromium Total ICAP/MS	ug/L	50		ND
Copper Total ICAP/MS	ug/L	1000		100
Hexavalent Chromium by 218.6	ug/L			0.064
Iron Dissolved ICAP	mg/L			ND
Iron Total ICAP	mg/L	0.3		ND
Lead Total ICAP/MS	ug/L	15		3
Lithium Total ICP	mg/L			ND
Magnesium Total ICAP	mg/L			ND
Manganese Total ICAP/MS	ug/L	50		ND
Mercury ICP/MS	ug/L	2		ND
Molybdenum Total ICAP/MS	ug/L			ND
Nickel Total ICAP/MS	ug/L	100		ND
Potassium Total ICAP	mg/L			ND
Selenium Total ICAP/MS	ug/L	50		ND
Silica	mg/L			ND
Silver Total ICAP/MS	ug/L	100		ND
Strontium ICAP	mg/L			ND
Thallium Total ICAP/MS	ug/L	2		ND
Total Hardness as CaCO3 by ICP	mg/L			ND
Uranium ICAP/MS	ug/L	30		ND

Analytes	Unit	Max Contamination Limit (MCL)	Raw Wastewater	Recycler Permeate
Vanadium Total ICAP/MS	ug/L			ND
Zinc Total ICAP/MS	ug/L	5000		78

ND = non-Detect
Source: Porifera Inc.

EPA Suite Analysis

EPA Suite analysis revealed excellent performance by the Recycler system in treating almost all test parameters (non-detect). The parameters listed in the Table 5 (below) show summarized values where the permeate was greater than non-detect.

Table 5: Results from EPA Suite Analysis Sample Grab

Parameter	Units	Raw Wastewater	PFO Recycler			MCL
		FO Feed	1P RO Perm	2P RO Perm	2P RO Perm	
2-Butanone (MEK)	ug/L	Confidential	140	93		
Acrylamide	ug/L		0.72	0.66		
Aggressiveness Index-Calculated	None		8.82	8.55		
Alkalinity in $CaCO_3$ units	mg/L		49	25		
Anion Sum - Calculated	mEq/L		6.1	0.56		
Beta, Gross	pCi/L		8.6	ND		
Bicarb Alkalinity as HCO_3 calc	mg/L		59	31		
Carbon Dioxide Free(25°C)-Calculated	mg/L		12	6.4		
Carbon disulfide	ug/L		1.2	2.6		
Cation Sum - Calculated	mEq/L		3.3	0.53		
Chloride	mg/L		180	2.1		500
Copper Total ICAP/MS	ug/L		2.6	ND	100	1000
Hexavalent Chromium by 218.6	ug/L		0.14	0.059	0.064	
Langelier Index - 25°C	None		-3.1	-3.4		
Langelier Index at 60°C	None		-2.6	-2.9		
Magnesium Total ICAP	mg/L		0.13	ND	ND	
Nitrate as Nitrogen by IC	mg/L		0.36	ND		10
Nitrate as NO_3 (calc)	mg/L		1.6	ND		45
Odor at 60°C (TON)	TON		17	17		3
pH (H3=past HT not compliant)	-		6.9	6.9		

		Raw Wastewater	PFO Recycler			
Parameter	**Units**	**FO Feed**	**1P RO Perm**	**2P RO Perm**	**2P RO Perm**	**MCL**
pH of $CaCO_3$ saturation (25°C)	-		10	10		
pH of $CaCO_3$ saturation (60°C)	-		9.5	9.8		
Potassium Total ICAP	mg/L		2	ND	ND	
Sodium Total ICAP	mg/L		74	12		
Specific Conductance	umho/cm		590	59		1600
Strontium 90 (sub)	pCi/L		<2	<2		
Strontium-90, MDA	pCi/L		0.566	0.546		
Strontium-90, Two Sigma Error	pCi/L		0.284	0.202		
Styrene	ug/L		2.3	0.84		100
Sulfate	mg/L		1.2	ND		500
Toluene	ug/L		1.4	ND		150
Total Dissolved Solid (TDS)	mg/L		200	45		1000
Total Nitrate, Nitrite-N, CALC	mg/L		0.36	ND		10
Tritium	pCi/L		<270	<270		
Tritium, Minimum Detectable	pCi/l		211	210		
Tritium, Two Sigma Error	pCi/l		204	203		
Turbidity	NTU		0.36	0.36		5
Iron Total ICAP	mg/L				0.016	0.3
Zinc Total ICAP/MS	ug/L		91	63	78	5000

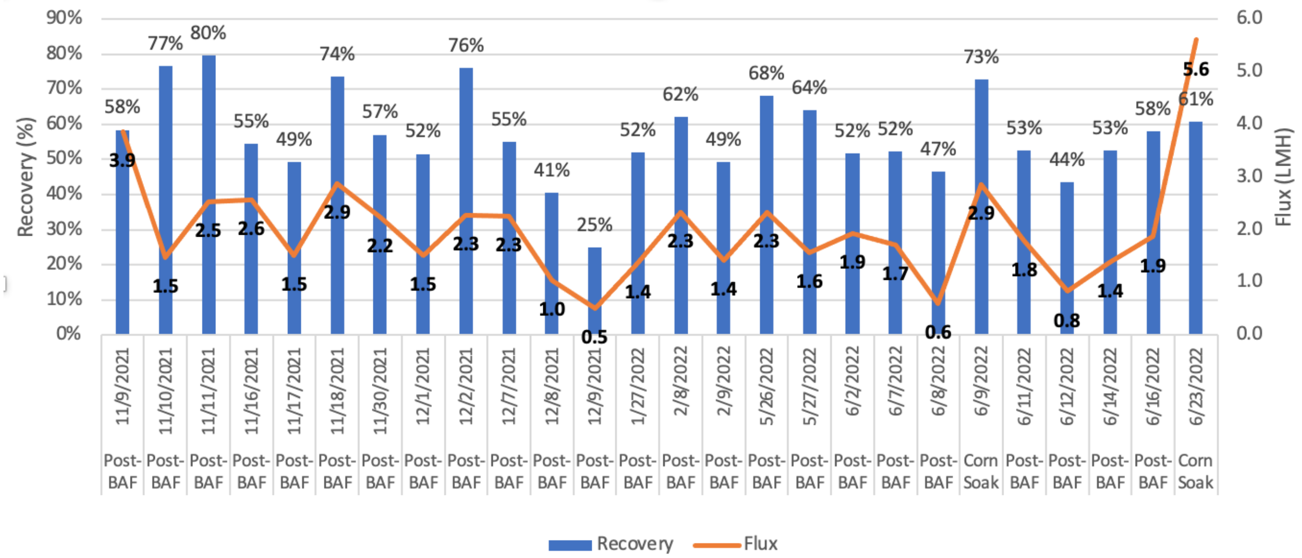
Source: Porifera Inc.

Continuous Data Collection Results

Flux and Recovery

Throughout the duration of the pilot, the Recycler system achieved an average flux of two gallons per minute, and an average recovery of 57 percent (target recovery was set to 50 percent). The longest continuous run was achieved between a three-day period from 12/7/2021 to 12/9/2021 before the system was shut down for maintenance (CIP). Periodic CIP was required to remove fouling caused by high solid loading. Figure 17 (below) summarizes key performance data points.

Figure 17: System Flux (LMH) and Recovery Percent



Credit: Porifera Inc.

Energy Consumption

To measure the power consumption of the system, an AccuEnergy real time power meter was fitted into both the FO and RO electrical enclosures, with current clamps around the main circuit breakers. The results are presented in Table 6.

Table 6: Energy Measurements, Projections, and Comparison

Metric	PFO Recycler System		Current Market Leading Technology
	Onsite Measurements	Commercial System Projections	Membrane Bioreactor (MBR) + RO with Ancillary Equipment
FO system pump efficiency	30%	50%	-
RO stage 1 pump efficiency	30%	90%	-
RO stage 2 pump efficiency	50%	85%	-
RO operating pressure [psi]	600	430	-
Total energy consumption [kWh/1,000 gallons permeate]	35.2	14.5	29.07

The "Total Energy Consumption" denotes how many kilowatt-hours (kWh) of electrical energy are required to produce 1,000 gallons of clean water.

Source: Porifera Inc.

Improving Power Consumption

System efficiency and power consumption can be improved up to 50 percent in commercial scale systems by:

- Using energy efficient drives and pumps
- Improving prefiltration
    - High solid loading in the feed stream can cause particulate accumulation on the FO membrane, thereby reducing membrane performance. To maintain the set recovery, the system will add more salt into the draw tank, increasing the energy consumed by the RO. Adapting a better prefiltration system will in-turn lower energy consumption by the RO.

Projected Operating Expenditure

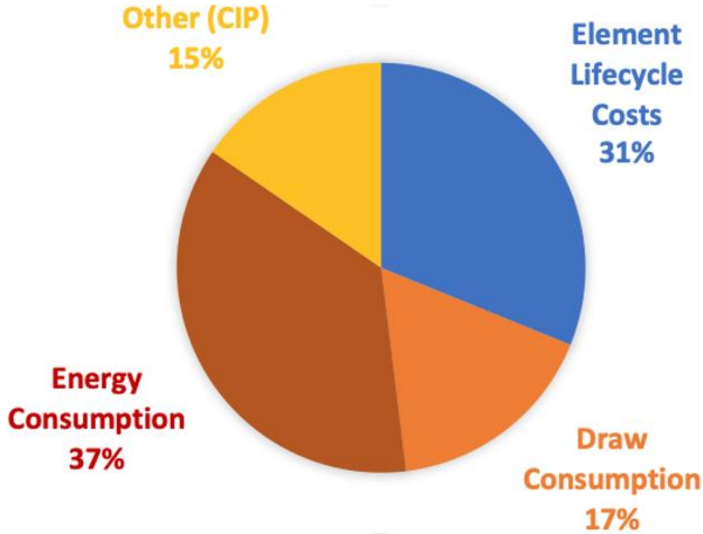
Porifera performed a techno-economic analysis to estimate the OPEX of this technology and compared it with current market leading technology. The projected cost savings of adopting the PFO Recycler system on a commercial scale compared to membrane bioreactors and RO is $214 OPEX savings per acre-foot of clean water produced (Table 7). The OPEX costs is dominated by energy consumption, followed by membrane costs (Figure 18).

Table 7: OPEX Projections per Acre-foot of Clean Water Produced

OPEX per Acre-foot of Permeate	PFO Recycler	MBR + RO
Element Lifecycle Costs	$ 703.93	$ 351.96 **
Draw Consumption	$ 382.16	
Energy Consumption*	$ 825.64	$ 1,657.62
Other (CIP)	$ 348.73	$ 464.97
Total	$ 2,260.46	$ 2,474.55

* Energy values for FO-RO are based on projections for a commercial system and a cost of $0.14/kWh
**Estimated membrane costs (not provided by MBR vendors). All other costs were provided for by MBR vendors.
Source: Porifera Inc.

Figure 18: OPEX Per Acre-foot of Clean Water Produced



Source: Porifera Inc.

Key Learnings

A good pre-filtration system is essential for a continuous, successful operation to improve:

1. Water reclamation (percent recovery)
2. Flux (LMH)
3. Energy consumption

During this trial two pre-filtration systems were explored. Unfortunately, due to the nature of the suspended starch in the feed, both filters did not perform as expected.

- System 1 – a polymer disc filter with an automatic backflush routine
    - Backflush cycles proved ineffective in removing the solids from the filter discs resulting in quick fouling of the system (Figure 19, left).
- System 2 – a stainless-steel screen filter with a motor-driven cleaning brush.
    - Although the screen itself did not foul, it allowed a large quantity of solids to be pushed through its filter screen, resulting in fouled FO elements (Figure 19, right).

The PFO Recycler System was ultimately piloted without prefiltration but since the conclusion of piloting for this Project Porifera has identified a different, more suitable prefiltration system through work with another customer.

Figure 19: Fouling on Prefiltration System #1 (Left) and on Prefiltration System #2 (Right)

Credit: Porifera Inc.

CHAPTER 4: Conclusion

Key Implications of the Project's Outcome for Commercial Markets

This Project successfully met its goal of demonstrating the PFO Recycler system's ability to treat starch-laden wastewater for a California-based food processor. Widespread market adoption of this technology will make water reuse for other food processors more economical and energy efficient compared to current leading technologies. Additionally, the PFO Recycler has several advantages over its competitors:

- It produces exceptionally clean water
- It requires lower energy to operate (up to 50 percent less than MBR at commercial scale).
- It requires a smaller footprint to operate.
- It is easier to scale the system size because no bioreactors are required.
- It has a wide pH operating range (2 to 11).
- No biological treatment is required.
- No brine disposal is needed.
- No waste produced goes to landfills.
- The concentrated waste stream produced by the system may be re-used on-site as animal feed or mixed with primary sludge.

Water Quality

The PFO Recycler produced permeate with exceptional water quality, with minimal TDS, TSS, Hardness, COD, and metals in the reclaimed water stream (that is, over 99 percent removal of contaminants).

Energy and OPEX Savings

Independent Energy measurements for the pilot scale equipment were comparable to current market leading technologies, with projected energy savings up to 50 percent, and OPEX savings up to 10 percent on a commercial scale system.

Benefits to California's Clean Energy Goals, with Intangible Ratepayer Benefits

As PFO technology gains momentum and wastewater reuse grows rapidly, the qualitative and intangible benefits to California ratepayers will grow correspondingly. These include:

- Providing unique solutions for water reuse that will increase water availability during droughts while increasing safety of the water supply.

- Improving groundwater and surface water resources (that is, more water at reduced salinity levels will be available for irrigation, more water will be available for power plant hybrid cooling projects etc.)
- High quality industrial reuse and potable reuse with softer and less salty water than standard non-potable recycled water (soft water improves energy efficiency of cooling towers, boilers, refrigeration, and other industrial and commercial equipment).
- Decreased water costs compared to desalination.
- Decreased water costs compared to more traditional sources (such as surface water) in drought prone regions for which costs continue to rise.
- Decreased pumping between Northern California and Southern California during non-drought years allowing more of the water from the State Water Project to be used for environmental restoration, agriculture, or hybrid cooling of power plants.
- Increased hydroelectric power during drought years from the state and federal hydroelectric systems if local municipalities can discharge reuse water directly into, or decrease diversions from, reservoirs that generate electricity.
- Environmental benefits including less diversion from rivers to improve fish habitat and other benefits related to water and/or temperature.

Key Learnings and Future Development Opportunities

Higher flux and water recovery can be achieved by exploring appropriate pre-filtration systems to reduce the solid loading in Porifera's membrane elements. A good pre-filtration system will help improve:

- Water reclamation (percent recovery)
- Flux (LMH)
- Energy consumption (kWh)

Reduced solids on the FO elements will allow the RO system to operate at a lower pressure, while reducing operating expenditure costs. Combined with an appropriate prefiltration system, Porifera can scale-up the Recycler system for commercial applications through its modular design by adding more membrane area and increasing the number of stages needed to treat larger quantities of wastewater. Future technology explorations include testing prefiltration via clarifiers, hydro cyclones, or microfiltration systems. Porifera has previously used microfiltration to achieve continuous FO-RO operation with high flux (six LMH) and high recovery (up to 90 percent) without the need for frequent CIPs. A combination of these technologies is currently being explored for a large commercial scale system to treat paper pulp fibers in wastewater.

GLOSSARY

Term	Definition
BAF	Bulk air flotation
BOD	Biological oxygen demand
CEC	California Energy Commission
COD	Chemical oxygen demand
CIP	Clean-in-place
EPA	Environmental Protection Agency
EQ	Pre-equalization
FO	Forward osmosis
kWh	Kilo Watts per hour
LMH	Liters per square meter per hour
MBR	Membrane Bioreactor
MCL	Maximum Contamination Limit
OPEX	Operating expenses
PFO	Porifera Forward Osmosis
PPM	Parts per million
psi	Pounds per square inch
RO	Reverse osmosis
TDS	Total dissolved solids
TSS	Total soluble solids

Project Deliverables

The Project Deliverables include:

- Final Report
- PFO System Maintenance and Operation Report
- Test Plan for PFO Recycler System
- Measurement and Verification Report
- Field Test Feedback Report
- Technology Transfer Report