# Technology Opportunities for Improved Nutrient Removal from Human Waste

**Emerging algae, electrochemical, and membrane technologies to improve smaller-scale treatment of domestic wastewater and fecal sludge**

**August 2020**

RTI Innovation Advisors

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## About this Report

Nutrient pollution negatively impacts oceans and inland water bodies. This report highlights emerging technologies that show promise for reducing the cost of treating nitrogen or phosphorus at smaller-scale, domestic wastewater and fecal sludge treatment facilities. The report focuses on three promising technology areas—algae-, electrochemical-, and membrane-based treatments.

Readers will gain an initial understanding of the challenges associated with nutrient treatment, emerging technologies that could meet these challenges, and specific technologies that represent opportunities for potential partnership or investment.

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# Acronyms

C = Carbon

EPA = Environmental Protection Agency

FO = Forward Osmosis

FS = Fecal Sludge

Gpd = Gallons per Day

GWT = Gross-Wen Technologies

IFAS = Integrated Fixed Film Activated Sludge

I-PHYC = Industrial Phycology

IX = Ion Exchange

KLD = Kilo Liters per Day

MABR = Membrane Aerated Biofilm Reactor

MGD = Million Gallons per Day

MBR = Membrane Bioreactor

MBBR = Moving Bed Biofilm Reactor

RAB = Revolving Algae Biofilm

RO = Reverse Osmosis

TN = Total Nitrogen

TP = Total Phosphorous

SBR = Sequencing Batch Reactor

SND = Simultaneous nitrification/denitrification

PAO = Phosphorous Accumulating Organisms

USD = U.S. dollars

VC = Venture Capital

WW = Wastewater

WWTP = Wastewater Treatment Plant



*Acronyms are defined in the text when they are first used.*

# Key Findings

## *Key Finding* 1 Standard wastewater and fecal sludge treatment methods can typically remove some nutrients.

Treatment is a key phase of the sanitation process where levels of nutrients like nitrogen and phosphorus can be reduced. Standard wastewater and fecal sludge treatment methods typically focus on reducing organic matter and pathogens, rather than on removing nutrients. However, these methods can typically remove some levels of nitrogen and phosphorus. For example, commonly used activated-sludge techniques use biological processes where microorganisms convert organic material and nutrients into biomass, which must be eventually removed. Using activated sludge, ~40% to >90% of both nitrogen and phosphorus can be removed from wastewater.[1]


[1] *USEPA, 2015*

## *Key Finding* 2 Additional nutrient removal is often required to meet regulatory requirements.

Although standard treatment methods can remove some nitrogen and phosphorus, additional removal is often required to meet nutrient discharge regulations for a given wastewater or fecal sludge facility. Existing technologies specifically targeting nutrient removal from human waste typically use one of the following processes:

- nitrification/denitrification
- partial nitrification/anaerobic ammonia oxidation
- enhanced biological phosphorous removal
- chemical precipitation
- adsorption

Each process has advantages and limitations that impact applicability at a given scale of treatment. For example, methods suitable for use in removing nutrients at a household scale are different than approaches at treatment plants serving an entire community.

## Key Finding 3

## Challenges often exist for adopting nutrient-removal technologies, including policy and cost hurdles.

Discharge regulations, rather than economic benefits from nutrient recovery, drive adoption of these technologies in developed and *some* emerging economies. Requirements can vary significantly by location and are often dictated by nutrient-input levels considered to be acceptable for local water bodies receiving treated effluent. However, in emerging economies where people may lack access to basic sanitation, nutrient removal is often insufficiently regulated. When regulations are in place and enforced, costs of implementing existing treatment solutions can present adoption challenges.

## *Key Finding* 4

## A need exists for lower-cost, better-performing nutrient-removal technologies at smaller, intermediate scales (e.g., <1 MGD).

Existing nutrient-removal solutions are often acceptable, from a cost/performance perspective, at large scales (e.g., >1 MGD). However, experts indicated that a need exists for lower cost, better-performing nutrient-removal technologies at smaller scales. This need is especially pronounced at "intermediate scales" (e.g., <1 MGD).* At intermediate scales, a significant need exists for technologies that are:

- Inexpensive to implement and operate—small communities in varying contexts often have a lower tax base to draw from for capital costs and fewer resources for operational costs.
- Non-energy-intensive—to reduce operating costs, reliance on a consistent power source for operation, and carbon footprint.
- Simple—to reduce need for highly-skilled labor for operation, need for maintenance, and chances of system failure.
- Less reliant on chemical inputs—to reduce operating cost.

*As noted in later slides, "intermediate scales" in the context of this report does not include household-scale treatment.

## *Key Finding* 5

## Emerging technologies show promise for reducing costs and improving performance at intermediate treatment scales.

At these intermediate scales, experts identified three emerging technology approaches that could be promising for meeting these needs:

- Algae—converts influent nutrients, including nitrogen and phosphorus, into new algae biomass. Biomass can be cultivated and harvested for disposal or reuse; further biomass processing may be pursued to achieve higher-value by-products.
- Electrochemical—electricity-driven reactions oxidize or coagulate ionic or organic nutrients. In electrocoagulation, coagulants may be generated from sacrificial electrodes. In electrolysis, ammonium may be oxidized to nitrogen gas or chloramines. Other variations exist.
- Membrane-separation—membranes selectively restrict the passage of solvents (like water) and solutes (like nutrients). This can result in solute-rich liquids on one side of the membrane. Processes can be driven by pressure (nanofiltration and RO), osmosis (FO), temperature (distillation), and electricity (electrodialysis).

# Background

# Focus of this Report

Nutrient pollution is harming aquatic ecosystems, leading to negative economic impacts, a decrease in biodiversity, and a threat to human health.

Many sources contribute to nutrient pollution, but contributions from human waste—like wastewater and fecal sludge—are particularly concerning. Currently, 26.6% of the world does not have access to basic sanitation services. Even when sanitation infrastructure is in place, human waste still significantly contributes to nutrient pollution. As populations and the demand on existing infrastructure and resources increase, the impact of nutrient pollution will continue to rise.

Governments around the world are moving to tighten nutrient effluent standards for treatment plants. As regulations are put in place, the need has emerged for simple, cost-effective nutrient treatment technologies for smaller-scale (treating <1 MGD) facilities.

In response to this need, RTI engaged with wastewater-focused utilities, investors, engineers, researchers, and technology providers to identify promising solutions. RTI identified algae, electrochemical, and membrane-separation systems as some of the more promising emerging technologies. We then conducted a global search for researchers and startups developing these technologies for the treatment of wastewater and fecal sludge.

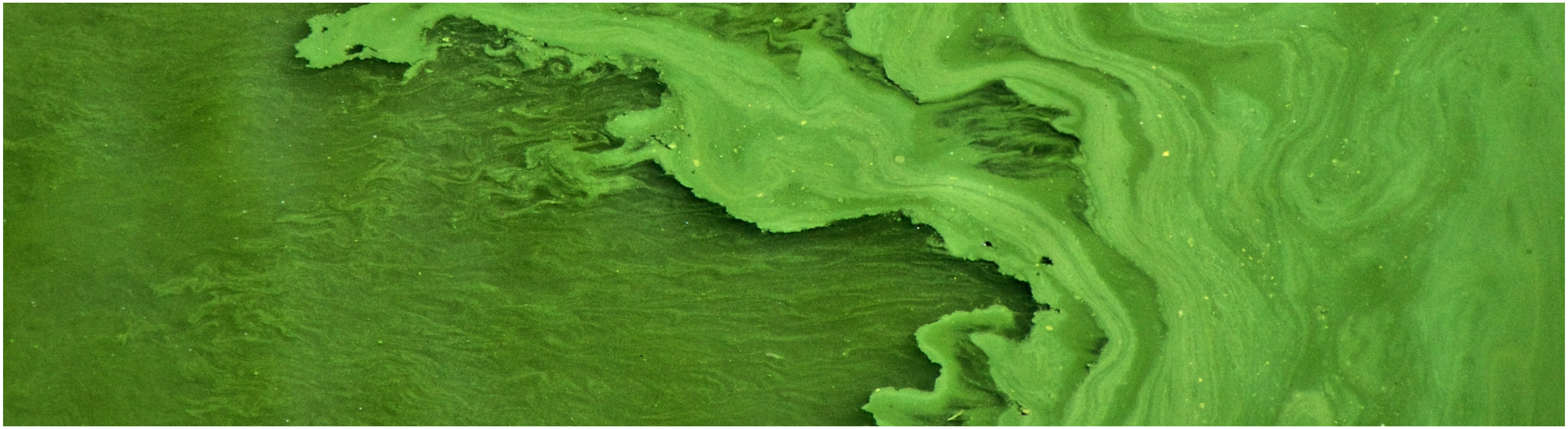
The results of our search, reported herein, provide a starting place for potential investors and partners to learn more about and engage with developers of emerging nutrient treatment technologies.

## This report **IS**…

- An overview of **algae, electrochemical, and membrane-separation technologies for** the removal of nutrients from human waste, including **wastewater (WW) and fecal sludge (FS).**
- **Focused on treatment at smaller scales (<1 MGD)**.
- **A starting point for potential investors and partners** to learn more about emerging technologies.

## This report **IS NOT**…

- **A comprehensive review of emerging technologies** (e.g., it does not include emerging technologies for other tech approaches, such as adsorption or precipitation).
- **A technoeconomic analysis** of emerging technologies.
- **A buyers-guide for utilities** or others seeking to procure treatment technologies.
- Focused on technologies for removal of **pollutants other than nitrogen and phosphorus.**



## Nutrient pollution is harming waterbodies.
### IMPACT OF NUTRIENT POLLUTION

Concentrations of nitrogen and phosphorus in receiving waterbodies are increasing. These increases harm aquatic and marine ecosystems through the process of eutrophication, an excessive growth of plant life and decay. Eutrophication ultimately leads to algae blooms, low dissolved oxygen content, and "dead zones" where organisms cannot survive.

**Eutrophication impacts waterbodies and the economies supported by them.** Eutrophication diminishes the abilities of coastal ecosystems to enable valuable tourism, recreation, and fishing activities. It also harms biodiversity.[1]

In **U.S. freshwaters alone**, a study by Dodds et al.[2] estimated that nutrient pollution could lead to **~$2.2B of annual economic losses**, including the following:

- $0.3B-$2.8B in property value losses
- $189M-$589M in fishing expenditure losses
- $182M-$567M in boating expenditure losses
- $813M in expenditures on bottled water
- $44M on conservation spending

The risk of nutrient pollution extends beyond economic impacts—directly threatening human health. Nitrates, a form of nitrogen found in fertilizers, can leach into groundwater. If ingested, nitrates can cause health impairments such as methemoglobinemia (blue-baby syndrome)—a deadly condition that starves blood of oxygen.[2] In India, more than half of districts have groundwater contaminated with nitrates.[3]

*You can read more about the impacts of nutrient pollution here.*

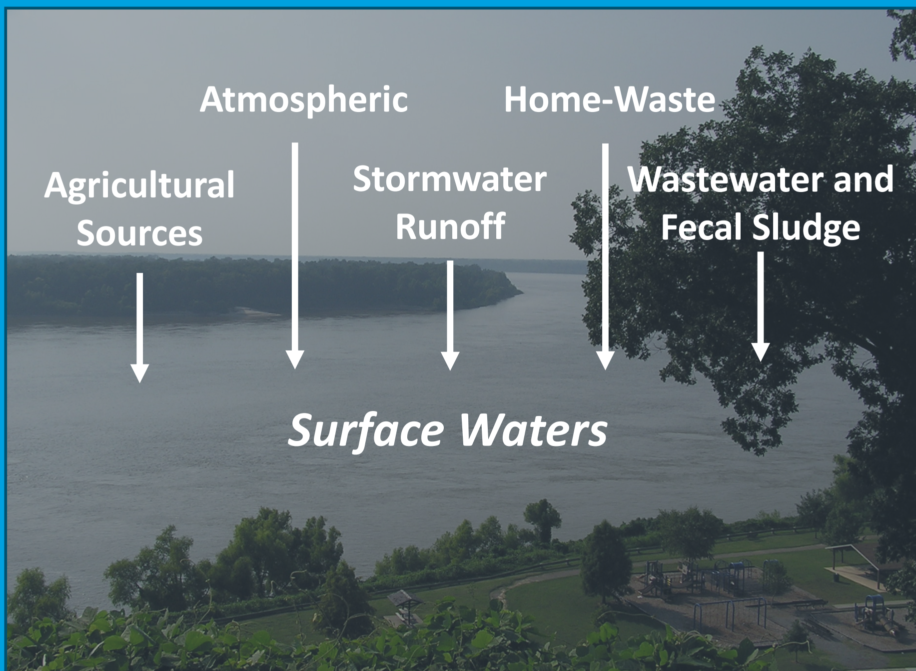


[1]*WRI 1*, [2]*WRI 2*, [3]*Times of India article*, *Image* by Mihály Köles on

## Many different sources contribute to nutrient pollution.

Nutrients can enter waterbodies from a variety of sources. The primary sources[1] of excess nitrogen and phosphorus include agriculture, stormwater, wastewater and fecal sludge, fossil fuels (increasing the amount of nitrogen in the air), and home-wastes such as fertilizers, pet wastes, and cleaning products.

### Primary sources of nutrient pollution




*In this study, researchers did not attempt to determine the leading contributing source of nutrient pollution.*

## Contributions from wastewater and fecal sludge are particularly concerning.

Nitrogen and phosphorous pollution from human waste, specifically WW and FS is particularly concerning. As of **2017, 32% of the world's population still lacked access to basic sanitation services.**[2] As a result, in many countries, households are the main source of nutrient pollution in urban areas.[3]

Even where sanitation infrastructure exists, WW and FS contribute to nutrient pollution. For example, in the United States:

- WW overflows from sewers can pollute the environment—the EPA estimates 75,000 sewer overflows occur each year.[4]
- FS (from onsite sanitation systems like septic tanks) can overflow and leach into the environment; a Florida study identified this as a major contributor to high levels of nitrogen in estuaries and downstream coastal reefs.[5]
- Treatment plants with insufficient nutrient treatment can discharge nutrient-rich effluents; U.S. WW treatment plants (WWTPs) process 34 billion gallons of WW daily,[6] but a 2011 study by the EPA showed most do not have permit or monitoring requirements for total nitrogen or phosphorous in effluent.[7]

Without intervention, population growth will significantly exacerbate nutrient pollution. A 2019 study forecasts **nutrient discharge to surface water will increase by 10–70% from 2010 to 2050.**[2] These increases occur even when assuming a 10–40% increase in enhanced nutrient removal treatment at WWTPs.

To safeguard the world's waterbodies, scalable practices and technologies are needed to reduce the impact of WW and FS nutrients.



[1]EPA, [2]JMP 2017 Report , [3]van Puijenbroek et al. 2018, [4]WSJ Article, 2017, [5]Science Daily 2018, [6]EPA 2, [7]EPA 3,, This photo by Shawn Rossi is licensed under CC BY-SA 2.0.

# Technologies exist today to remove nutrients from human waste.

**Biological Processes**

**Aerobic processes** convert organic compounds and nutrients, like nitrogen and phosphorus, into biomass in the presence of oxygen.

**Anoxic processes** convert nitrate-bound nitrogen to molecular nitrogen gas in the absence of oxygen.

**Anaerobic processes** convert organic compounds to methane and organically-bound elements, like nitrogen and phosphorus, to simple ions like ammonium and phosphate, in the absence of oxygen.

**Phototrophic processes** use photosynthetic organisms to convert carbon dioxide and nutrients, like nitrogen and phosphorus, into biomass.

**Physical & Chemical Processes**

**Membrane-separation processes** selectively restrict the passage of solvents (like water) and solutes (like ions and solids) through membranes.

**Precipitation processes** add material (like salts) to WW to precipitate out target ions through a crystallization reaction.

**Adsorption processes** attract ions from WW to the surface of an adsorbent, where they are held by intermolecular forces; the absorbent may be flushed for reuse and the ions may be recovered.

**Thermal processes** operate at high-temperatures and reduce the water content of WW, creating a range of nutrient-rich co-products.

**Oxidation processes** oxidize organic compounds and/or nutrients to produce nitrogen gas and/or trap nutrients in biosolids.

The most common biological and physical/chemical processes are described to the left.* Existing treatment technologies employ one or a combination of these processes to remove nutrients from human waste.

During the treatment of wastewater and fecal sludge, liquids and solids are typically separated first. Nutrient-removal technologies most commonly target treatment of the liquid portion of the waste following separation.

* Appendix A provides an overview of some of the more common nutrient treatment technologies that leverage these processes.

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## Adoption of nutrient removal technologies is regulatory driven…

"Nutrient treatment is a **regulatory-driven area** right now **for both nitrogen and phosphorus**."

*Partner—VC firm with a focus on water technology*[1]

There is a **recent driver for the adoption of phosphorous removal systems**—the new **regulatory burden.**"

*Sanitation technology researcher*[1]

"The **economics aren't there** to make anyone want to recover nutrients [for reuse]."

*Sanitation technology researcher*[1]

## …and even when regulations are passed, adoption can present cost challenges.

"For the most part, operators don't have lots of resources for nutrient treatment. So, there is a **need for systems that are simple to operate and not expensive to implement."**

*WW Expert—Leading engineering design firm*[1]

"Many publicly owned treatment works have added **treatment processes for extensive nutrient removal**, but these upgrades **are not affordable** or necessary **for all facilities**."

*WW Expert—Leading engineering design firm*[1]

"**Financing and institutional challenges** [related to retrofitting WWTPs] **are the main challenges facing nutrient treatment** improvements at WWTPs in Malaysia."

*Consultant & Expert on Malaysian WW*[1]



*1. Interviews conducted by RTI*

## The cost of nutrient removal is particularly challenging at intermediate scales, where there is a significant need for lower-cost, higher-performing technologies.

Interviews with utilities, WW engineering firms, investors, and researchers indicate a need for lower-cost, better-performing technologies for removing nutrients at intermediate-scale facilities. As such, there is an opportunity for technology providers and investors at this scale. In the United States, >80% of WWTPs treat <3,780 m3/d (as of 2015), although they only treat <10% of WW by volume.[1]

*Scale of wastewater treatment*

### Household Scale (<6 m3/d)[2]

- Household-scale nutrient treatment poses significant cost challenges when leach-field designs cannot meet standards.
- Nutrient-treatment at the household scale **may not make economic sense** in the near-term when compared to transport of waste for offsite treatment.

### Intermediate Scale (>=6 m3/d to ~4,000 m3/d)[2,3]

At this scale, there is a **significant need for technologies that are:**

- **Inexpensive to implement and operate**—small communities in varying contexts often have a lower tax base to draw from for system capital costs and fewer resources for operational costs.
- **Non-energy-intensive**—to reduce operating costs, reliance on a consistent power source for operation, and carbon footprint.
- **Simple**—to reduce need for highly-skilled labor for operation, need for maintenance, and chances of system failure.
- **Less reliant on chemical inputs**—to reduce operating cost.

### Centralized, Large Scale (>4,000 m3/d)[3]

- At this scale, a common approach is to adapt conventional activated-sludge systems for nutrient removal.
- Innovations/developments largely focus on process modifications for reducing costs and/or improving performance.
- Relatively new precipitation and membrane aerated biofilm reactors (MABR) show promise.
- Large-scale **technologies are adequate/mature.**

[1]Lux Research, 2015, [2] https://www.epa.gov/uic/large-capacity-septic-systems, [3]RTI interviews

# IT IS TIME TO INVEST IN THE DEVELOPMENT OF NUTRIENT REMOVAL TECHNOLOGIES.

As the impact of nutrient pollution is increasingly felt across the globe, regulators are acting to impose new discharge permits on WW treatment facilities.

Existing technologies are effective at large scale, but smaller facilities can struggle with the costs of *meeting new discharge permit levels.*

Effective, simple, lower-cost technologies must be developed to meet this need.

# Opportunities

# Algae, electrochemical, and membrane-separation technologies show promise for nutrient removal at intermediate scales.


**What we heard**

*"We have cautious optimism about algae after tracking it for 10 years now. Even with lighting constraints, we think it will scale-down better than precipitation."*[1]

**How it works**

Algae converts influent nutrients, including nitrogen and phosphorus into new algae biomass. Biomass can be cultivated and harvested for disposal or reuse; further biomass processing may be pursued to achieve higher-value by-products.


**What we heard**

*"I'm most bullish on electrochemical systems in decentralized treatment. They are inherently targeted for concentrated waste streams."*[2]

**How it works**

Electricity-driven reactions oxidize or coagulate ionic or organic nutrients. In electrocoagulation, coagulants may be generated from sacrificial electrodes. In electrolysis, ammonium may be oxidized to nitrogen gas or chloramines. Other variations exist.


**What we heard**

*"Membrane separation is particularly interesting for applications requiring a small footprint, and the technology is ready to be piloted now."*[2]

**How it works**

Membranes selectively restrict the passage of solvents (like water) and solutes (like nutrients). This can result in solute-rich liquids on one side of the membrane. Processes can be driven by pressure (nanofiltration and RO), osmosis (FO), temperature (distillation), and electricity (electrodialysis).

[1]*RTI interview with nutrient recovery expert at leading wastewater engineering consulting firm,* [2]*RTI interviews with academic sanitation technology researchers*


*"There's a lack of non-energy-intensive options to get from 15 mg/L to 5 mg/L of TN – to meet new permit limits. Algae might be able to fill this gap."[1]*

## Overview

After pretreatment, algae converts nutrients, including nitrogen and phosphorus into new algae biomass. Biomass can be cultivated and harvested for disposal or reuse; further biomass processing may be pursued to achieve higher-value end products.

## Common Advantages

- Can recover both nitrogen and phosphorus.
- Nutrient removal can be low energy, requiring light and mixing instead of aeration.
- Enables high-value end products like turf fertilizer or protein-rich feed.
- Offers a low carbon footprint, as phototrophic process fixes $CO_2$.

## Common Limitations

- Biomass dewatering and processing can be high cost.
- Can be land intensive; shallow-depth reactors used to increase light and performance.
- Intensifying treatment can lead to higher costs.
- Techno-economics are not yet well understood.

## Example Permutations

**Open, suspended-growth:** Often known as raceways, these systems are common in outdoor applications. Paddles may keep algae suspended for sunlight access, and shallow depths enable light penetration.

**Closed, suspended-growth:** Often known as photobioreactors, these systems have smaller operational volumes but higher biomass densities than open systems.

**Attached-growth**: Emerging systems encourage algae to grow on a surface, enabling high culture density and easier removal after treatment is complete.

**Photogranules:** Algae-containing photogranules are roughly spherical biological materials being investigated for WW treatment. They show potential to remove chemical oxygen demand and other pollutants from WW without external aeration.

## Example Tech Developers

Global Algae Innovations, and Microbio Engineering offer raceway technologies. AQ Wind's system incorporates a raceway downstream of their attached-growth stage.

CLEARAS Water Recovery broke ground on their first full-scale installation in 2019, and Industrial Phycology has pilot-tested on municipal WW in the United Kingdom.

Gross-Wen Technologies recently made their first commercial sales; Ariel University research was spun into startup yAlgae.

University of Massachusetts Amherst researchers are leading development for WW treatment applications. Their work was summarized here in a 2019 webinar.

*The described permutations and example developers are not exhaustive of all algae-based wastewater and fecal sludge treatment approaches.*



*[1]RTI interview with nutrient recovery expert at leading wastewater engineering consulting firm; TN=Total Nitrogen.*


*Illustrative Example*

# Revolving Algae Biofilm

## Gross-Wen Technologies

Gross-Wen Technologies uses its patented treatment technology, known as the revolving algal biofilm (RAB) system, to cost-effectively address new wastewater permits.

The RAB system uses vertically-oriented conveyor belts that grow algae on their surface. While the algae grows it “eats” nitrogen and phosphorus from the effluent. It also uses carbon dioxide from the atmosphere and sunlight to rapidly grow algae biomass. Algae is harvested from the belts and may be further processed into pellets, which can be used for fertilizer or bioplastic applications.

The company has completed pilots and demonstration projects across the United States, including in Illinois, Wisconsin, and Iowa. They recently completed their first commercial sales in Iowa—all to sewage treatment plants treating <1 MGD.

Related patents include US20190248688A1 and US20140273172.

Learn More



*Image from Gross-Wen Technologies*


*Illustrative Example*

# The I-PHYC Solution

## Industrial Phycology

Industrial Phycology's patented I-PHYC solution uses algae and cutting-edge technology to extract pollutants from wastewater, which the algae uses as nutrients. Unlike other systems that rely on light being shone on the surface of the algal mixture, I-PHYC uses custom lighting elements to drastically reduce required tank size—enabling smaller treatment footprint.

The system's modular design can be scaled for industrial use and adapted to the needs of wastewater operators. The system can enable removal of multiple pollutants, reduced carbon emissions, biomass production, cost efficiency, and a chemical-free treatment solution.

The company recently secured £550k in funding to help roll out the technology. This follows recent successful trial results in partnership with Weston-Super-Mare Sewage Works—where the system demonstrated phosphorous removal up to 97% and ammonia and nitrate removal up to 95%.

Related patents include US20150329395.

Learn More

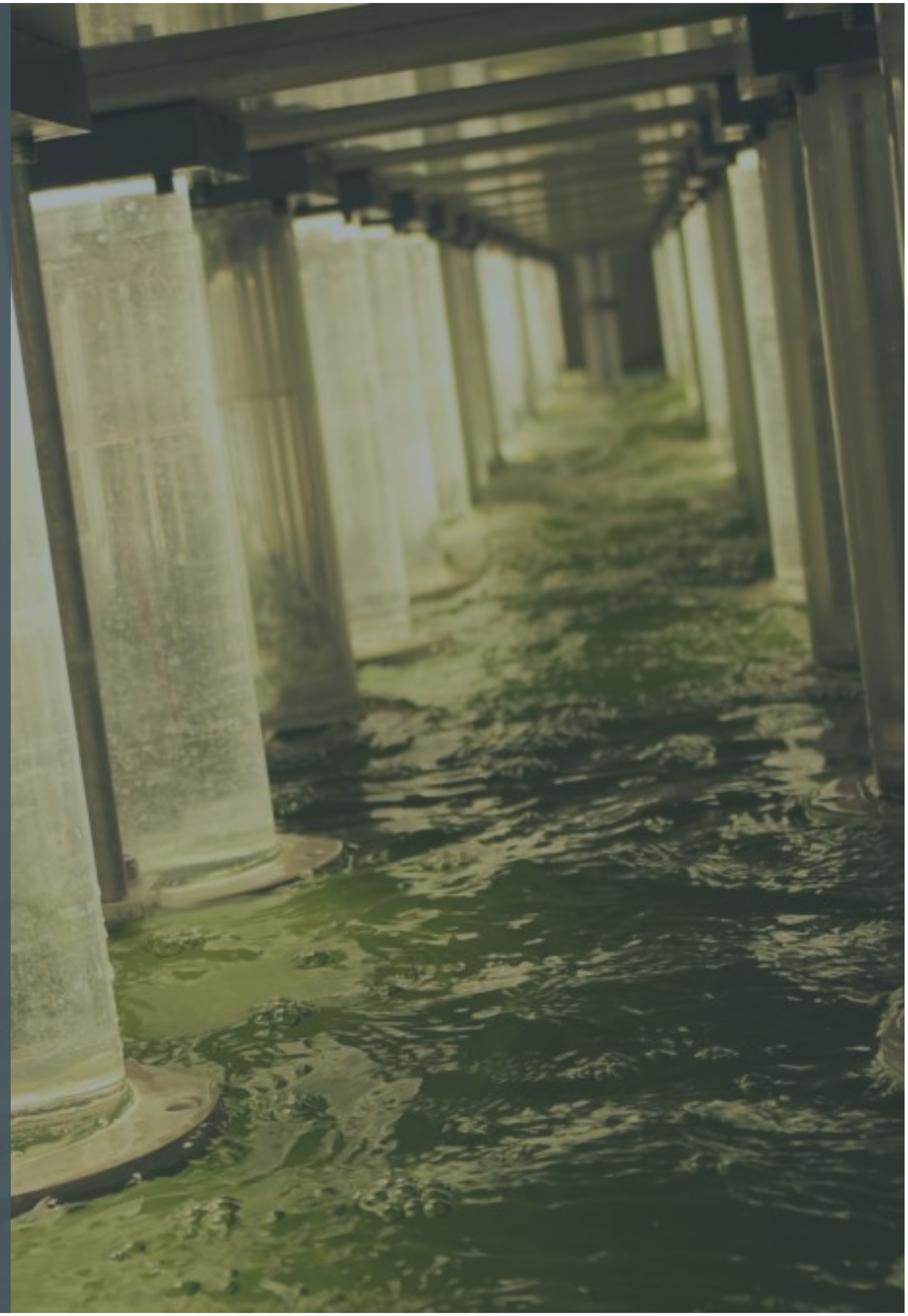


*Image from I-PHYC*


*Illustrative Example*

# Oxygenic Photogranules

## University of Massachusetts Amherst

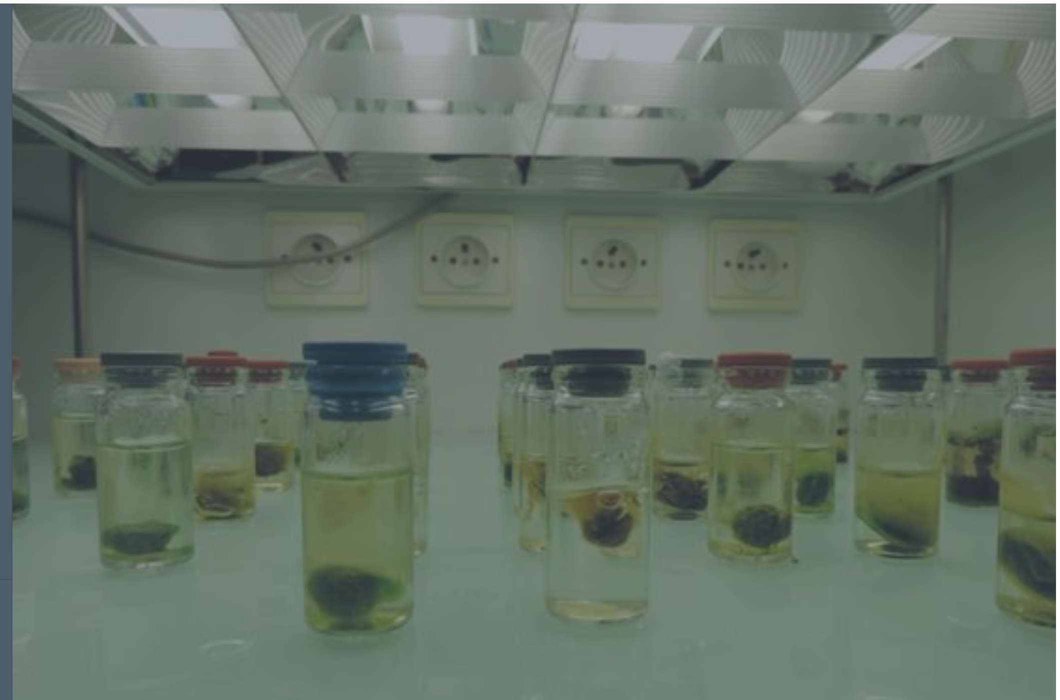
Oxygenic photogranules (OPGs), also called algal-sludge granules, are granular matter that include phototrophic and non-phototrophic microorganisms. OPGs can be mixed with wastewater to treat carbon, nutrients, and other pollutants, such as viruses and heavy metals, without external aeration.

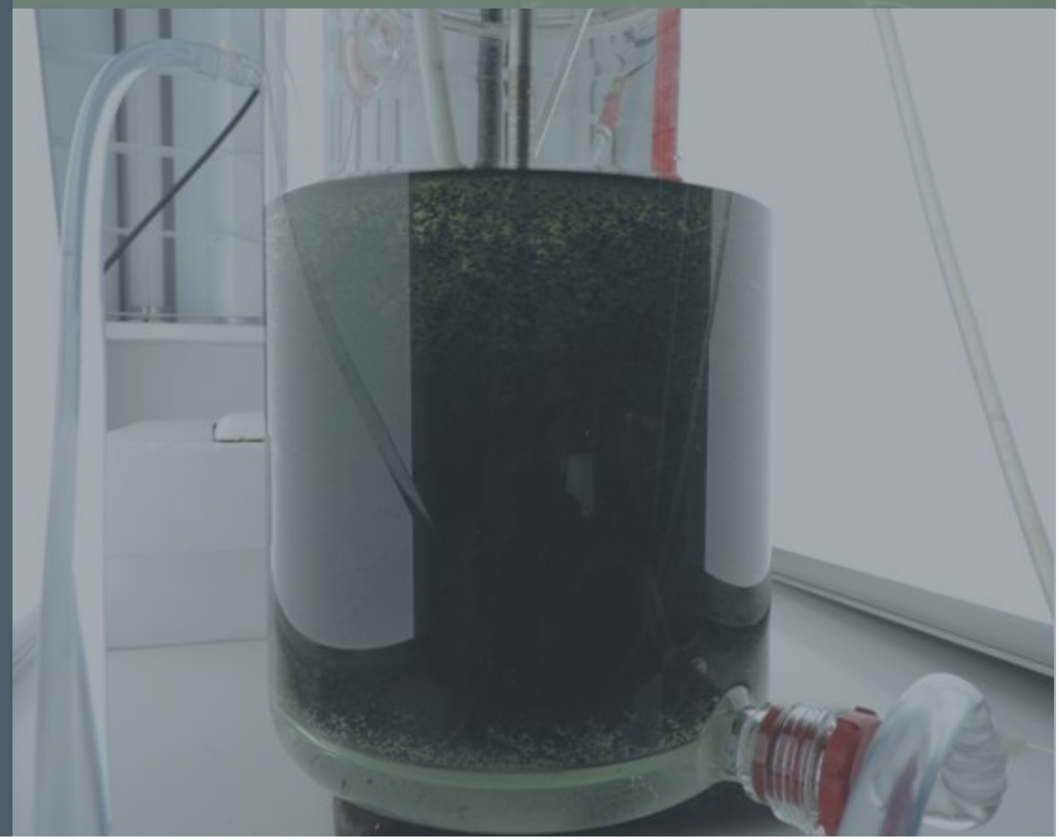
The potential to reduce the need for aeration in wastewater treatment could lead to significant energy savings. As Professor Park notes, current wastewater treatment methods are energy intensive, accounting for >1% of all U.S. energy expenditures each year[1] and aeration incurs the highest energy demand in wastewater treatment.

Although the study of OPGs to substantially reduce energy usage in wastewater treatment is relatively new, initial tests are promising. Park and his team are working now to scale up the technology.

Related patents include US10189732B2.

**Learn More**







[1]WEF Presentation in 2018, Images provided by Professor Park.

**Electrochemical-** based treatment

*"I'm most bullish on electrochemical systems in decentralized treatment. They are inherently targeted for concentrated waste streams."*[1]

## Overview

Electrochemical reactions leverage an electric current to drive electrolysis, flocculation, or other removal processes for nutrients from effluents. These treatment technologies are distinct from treatment technologies that capture energy for re-use to reduce treatment costs.

## Common Advantages

- Fast treatment compared with biological processes.
- Solid-state design can lead to simple operation, especially in decentralized settings.
- Less sensitive to environmental conditions like low temperatures (unlike biological processes).

## Common Limitations

- Can be energy intensive, which can impact operating costs.
- May require the use of expensive consumables, such as sacrificial electrodes; lifetime of key components drives cost value-proposition.
- Metal or other waste may complicate disposal of biosolids in some configurations.

| Example Permutations | Example Tech Developers |
| --- | --- |
| **Electrolysis:** An electrochemical reactor is configured to chemically decompose ionic and organic components of an influent stream, which can result in the off-gassing of nitrogen and/or precipitation of phosphorus. | Current Water Technologies offers an ammonia-targeted technology. Caltech and partners have developed an electrochemical reactor where electrolysis of chloride into chlorine gas *in situ* can lead to decomposition of WW. WeCo's system contains an electrolyzer (although details are unclear to RTI). In a unique variation, Princeton researchers recently isolated bacterium *Acidimicrobiaceae* sp. (A6) and have shown that Feammox—or anaerobic ammonium oxidation under iron reducing conditions—can occur with the microbe acting as part of an electrolysis cell; this discovery could pave the way for anaerobic, ammonium-oxidation systems driven by reducing electrodes instead of Fe(III). |
| **Electrocoagulation:** Electricity oxidizes a sacrificial electrode to form coagulants that can remove influent contaminants, including phosphorus, by capturing them in a floc or solids; significant oxidation can lead to nitrogen off-gassing in this process. | Startups Indra Water and Electro-Chemistry offer variations of electrocoagulation, as do large firms including Terragon, Genesis Water Technologies, Boydel WW Technologies, and FT Water Solutions. The rate at which the electrode may be consumed in these systems varies significantly based on system design, influent, and other factors. |

*The described permutations and example developers are not exhaustive of all electro-chemical-based wastewater and fecal sludge treatment approaches.*



[1] *RTI interview with interviews with academic sanitation technology researcher*

Electrochemical-
based treatment

*Illustrative Example*

# The Rigby System

## Electro-Chemistry, LLC

From domestic sewage to driller mud and food processing grease, Electro-Chemistry's patented Rigby System purifies wastewater using direct current to dissociate water and other molecules—removing both organic and inorganic compound and killing 100% of coliform bacteria. For organic compounds, voltage breaks break down chemical bonds to produce smaller molecules, often just carbon dioxide and water. For inorganic solids, direct current electrons destabilize the particles in colloidal suspensions, preventing settling and successfully separating contaminants, including cement dust, carbon, silt, and laundry dirt.

In a municipal sewage study in Virginia, the system was used as a tertiary denitrification step to achieve 0.1 mg/L of total nitrogen in effluent.

After a successful 2018 pilot, the EPA purchased and installed a *Rigby System* at their Environmental and Test Laboratory in Cincinnati, Ohio.

Related patents include US10662087B2.

**Learn More**



*Image from David Rigby, Electro-Chemistry, LLC*

Electrochemical-based treatment

*Illustrative Example*

# Feammox

## Princeton University

Autotrophic Actinobacteria *Acidimicrobiaceae*-bacterium, named A6, have been linked to anaerobic ammonium ($NH_4^+$) oxidation under iron reducing conditions. These organisms obtain their energy by oxidizing $NH_4^+$ and transferring the electrons to a terminal electron acceptor (TEAs). Under environmental conditions, the TEAs are iron oxides [Fe(III)], which are reduced to Fe(II); this process is known as Feammox

A research group at Princeton University, who recently isolated the A6 strain, has demonstrated that alternative forms of TEAs—like electrodes in a biochemical system—can be used by A6 to sustain $NH_4^+$ removal. This discovery could pave the way for future anaerobic ammonium (or other contaminant) removal processes using A6.

These processes could be attractive as an energy efficient form of ammonium removal as they do not require aeration or heating of the wastewater in temperate zones. The research group is working to scale up the technology.

Related patents include US10479712B2.

**Learn More**



Photo from Melany Ruiz

**Membrane-separation-**
based treatment

> *Membrane separation is particularly interesting for applications requiring small footprint, and the technology is ready to be piloted now.”*[1]

## Overview

Membranes selectively restrict the passage of solvents (like water) and solutes (like ions and solids). This can result in solute-rich liquid on one side of the membrane.

## Common Advantages

- Potential for high nutrient removal.
- Low footprint/space requirement.
- Produces separated stream of concentrated nutrient ions, enabling reuse.
- Removes need for precipitation chemicals.

## Common Limitations

- Lack of detailed technoeconomic analyses related to energy demand, costs, and robustness.
- Cost and O&M impacts from membrane fouling.
- Can require elevated temperature and pressure.

| Example Permutations | Example Tech Developers |
|---|---|
| **Pressure-driven:** Pressure drives water through a membrane, and solutes of a certain size are contained. Examples include nano filtration, ultra filtration, and reverse osmosis (RO). | Pure Water Monterey utilized RO to manage nitrogen. Cerahelix’s pico filtration technology was combined with electrocoag to remove nitrogen and phosphorus from dairy WW. Digester Organics’ two-step RO tech has been demonstrated in dairy WW. |
| **Osmotically-driven:** In forward osmosis (FO), osmotic pressure generated by a draw solution draws water across a semipermeable membrane. | BLUE-tec’s FO system is being evaluated for nutrient extraction in 0.2–2 m3/hour pilots. Hollow-fiber FO tech developed by Nanyang Technical University has been licensed by de.mem, with a focus on industrial WW. |
| **Thermally-driven**: In membrane distillation, hydrophobic membranes provide barriers to liquid phase material, allowing vapor (e.g., water vapor) to pass. | Vuna’s membrane distillation process has been piloted to distill nitrogen-rich liquid fertilizer from urine. BLUE-tec offers membrane distillation technology as well. |
| **Electrically-driven:** In electrodialysis, ions from a feed solution are passed through an ion-exchange membrane under the influence of an applied electric potential. | Stanford researchers demonstrated electrochemical stripping for nitrogen recovery. Triangle Environmental was awarded an EPA grant in 2020 to apply their electro dialytic nutrient recovery tech to decentralized WW streams. Saltworks piloted electrodialysis reversal tech and achieved 95% ammonia reduction from WWTP centrate. |

*The described permutations and example developers are not exhaustive of all membrane-separation-based wastewater and fecal sludge treatment approaches.*



[1] *RTI interview with interviews with academic sanitation technology researcher*

**Membrane-separation-**
based treatment

## *Illustrative Example*

# Electrochemical Stripping to Recover Nitrogen

## Stanford University

Dr. William Tarpeh's electrochemical stripping approach combines electrodialysis and membrane stripping to selectively recover nitrogen from nitrogen-rich wastewaters.

Demonstrated at a lab scale with urine in 2018, the technology selectively recovered nitrogen with 93% efficiency—requiring 30.6 MJ of energy per kg N recovered, which is competitive with existing nitrogen removal technologies.[1] In 2019, the technology was shown to work across a variety of concentrations and temperatures.[2]

Tarpeh's lab is working now to pilot and scale up the technology, both through partners and facilities at Stanford and through partnership with DELVIC Sanitation Initiatives in Senegal.

Learn More



1. *pubs.acs.org/doi/pdf/10.1021/acs.est.7b05488,*
2. *www.sciencedirect.com/science/article/abs/pii/S0043135419310000?via%3Dihub*

*Photo by Anna Kogler*

# BE PART OF THE SOLUTION

- **Act NOW** as governments around the world are introducing new nutrient-focused permit requirements; action is needed to ensure cost-effective solutions are adopted.
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RTI Innovation Advisors is a division of RTI International, an independent, nonprofit research institute dedicated to improving the human condition. We combine scientific rigor and technical expertise to deliver solutions to the critical needs of clients worldwide.

# Appendix A – Existing Methods for Nutrient Removal

# Biological and physical/chemical processes each have their own inherent benefits and limitations.

| | Biological Processes | Physical/Chemical Processes |
|---|---|---|
| **Advantages** | • Lower cost<br>• Often lower energy | • Rapid and repeatable |
| **Limitations** | • Relatively slow<br>• Microbes may be disrupted<br>• Potential challenges implementing at very small scales | • High consumables<br>• High waste products<br>• High temperature and pressure |
| **Reaction speed** | • Liquid (minutes to hours)<br>• Solids (days to weeks) | • Liquid (seconds to minutes)<br>• Solids (minutes to hours) |
| **Energy input** | • Low to moderate | • High |
| **Operating conditions** | • Ambient temperature and pressure | • Often highly elevated temperature and pressure |
| **Safety risks** | • Low to moderate (varying based on microbes used) | • High (if high temp/pressure or if toxic chemicals used) |
| **Consumables** | • Low to moderate | • High |
| **Waste products** | • Low to moderate | • High (metals, oxidants) |

High-level comparison of biological and physical/chemical processes for nitrogen and phosphorous removal.

Innovative technologies offering variations on these processes may mitigate disadvantages described here.

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## Nutrient removal technologies leverage these processes to treat human waste.

On the following slides, an overview of **some of the most common technologies** currently used for nutrient removal from human waste, like WW and FS, are provided. The overview is not intended to highlight the best emerging technologies in these categories. Rather, it is intended to provide readers new to nutrient removal technologies an initial understanding of existing processes.

### Technologies for nutrient removal from wastewater

| | **Nutrient Focus** | | **Process Used to Remove Nutrients** | |
|---|---|---|---|---|
| **Generic technology name** | *N* | *P* | *Biologic* | *Physical/Chemical* |
| Nitrification/denitrification | • | | • | |
| Partial nitrification/anaerobic ammonia oxidation | • | | • | |
| Enhanced biological phosphorous removal | | • | • | |
| Algae-based treatment | • | • | • | |
| Constructed wetlands | • | • | • | |
| Air stripping | • | | | • |
| Breakpoint chlorination | • | | | • |
| Chemical precipitation | | • | | • |
| Adsorption media | • | • | | • |
| Membrane separation | • | • | | • |
| Electrochemical treatment | • | • | | • |

*The described nutrient removal, permutation, costs, technologies and technologies providers are not exhaustive.*

*Technology Overview*

# *Nitrification/Denitrification*

*Typical Nutrient Removal*

| N | P |
|---|---|
| **High**<br>80%[4] to >95%[1] at US sewage treatment plants | **N/A**<br>although many processes incorporate P removal |

## Overview

This is a biological treatment process. First, ammonium and nitrite are oxidized by autotrophic bacteria to form nitrate (nitrification) under aerobic conditions; then heterotrophic microorganisms reduce nitrate to form nitrogen gas (denitrification) under anoxic conditions.

## Common Advantages

- Provides most cost effective and common method for N removal from wastewater
- Can achieve target effluent TN in many cases

## Common Limitations

- May rely in energy input and/or external carbon sources to achieve target effluent TN
- Has relatively long reaction time
- Can require large footprints and other factors that present financing challenges

## Common Permutations

Variations range in complexity, footprint, nutrient removal efficiency, and other factors. The most common system variations at WWTPs are suspended growth (e.g., Modified Ludzck Ettinger, Bardenpho, oxidation ditches, SBR and others)[2]; attached growth and hybrid systems (e.g., IFAS, MBBR, MBR, and others) are also used.[2] Nitrification/ denitrification may occur in sequenced reactors or simultaneously—such as in simultaneous nitrification/denitrification (SND)—within the same reactor if both aerobic and anoxic zones exist; this can occur in oxidation ditches and membrane aerated biofilm reactors (MABRs).

## Cost Considerations

Costs vary based on existing infrastructure, land availability, technology selected, facility size, and other factors. EPA[3] notes achieving <0.6-1.4 mg/L TN— at 94–98% removal efficiency—costs 1.27-3.58 *USD/gpd in capex and 0.05-0.09 *USD/gpd in opex using variety of biological systems and filtration. They noted 3–8 mg/L TN (79-92% removal efficiency) can be achieved for <0.1-94.4 8USD/gpd capex and <0.01–1.85 *USD/gpd capex using a range of biological process variations.

## Illustrative Technologies and Providers

Engineering firms, like Black & Veatch and Stantec, offer clients a variety of nitrification / denitrification process variations. In a suspended growth process[4] variation, microorganisms are suspended in WW. An anaerobic process, commonly the activated sludge process, degrades organic matter first; then denitrification occurs in an anoxic tank. Settled biomass is return to aeration or removed.

In an emerging variation, MABRs are offered by Dupont, Suez, and Fluence. MABR enables simultaneous nitrification/denitrification within a membrane-attached biofilm layer. System design enables low-energy oxygenation, small footprint, and other benefits. A 0.11 KLD installation achieved 10 mg/L TN in a one-year pilot.[5]



[1]EPA 2 , [2]EPA 1, [3]EPA 1 *(these costs in 2012 dollars [4]HAMK 2018, [5]Fluence pilot,), [6]EPA 3 and assuming influent TN of 50 mg/L for Table 2-1 values

*Technology Overview*
# *Partial nitrification – anaerobic ammonia oxidation*

*Typical Nutrient Removal*

| N | P |
|---|---|
| **High**<br>70% to >90% TN removal[1] | **N/A**<br>though many processes incorporate P removal |

## Overview

This is a biological treatment process. First, ammonia oxidizing bacteria oxidize half of available ammonia to produce nitrite, in a process called partial nitrification or nitritation; then, annamox bacteria oxidize ammonia using nitrite to produce N gas (without the organic C substrate required for conventional, heterotrophic denitrification).

## Common Advantages

- Lower energy per N removal, as the process requires less oxygen
- Lower external carbon requirement
- Lower alkalinity demand

## Common Limitations

- Slow process due to low growth rate
- Sensitive to operating conditions including pH, temperature, and others
- High capex

*The described nutrient removal, permutation, costs, technologies and technologies providers are not exhaustive.*

## Common Permutations

Typically utilized as a side-stream process for nitrogen removal, although mainstream deammonification and nitrite shunt variations are emerging.[2] Proprietary technologies vary in configuration and include upflow granular sludge beds, granular sludge SBRs, single or multi-stage MBBR, and 2-stage SBR or tanks with clarifiers.

## Cost Considerations

Systems typically have a high capex but offer opex benefits that can enable cost recovery in some cases. In one study, DEMON® system were demonstrated to payback costs over a 9-year period, saving one facility $8.5M USD/year from reduced methanol, alkalinity, and sludge processing.[3]

## Illustrative Technologies and Providers

Available from at least five providers and installed at >175 sites as of 2017.[3] Suppliers of suspended growth SBR variations include Suez and World Water Works. The latter's DEMON® technology provides N removal via deammonification in either continuous or SBR operating modes. It demonstrated 80% ammonia removal from side stream wastewater at a 56KLD plant on one study.[4]

Veolia is a provider of an attached growth and MBBR variation. In their ANITA™ Mox process, the attached growth biofilm contains the reaction;[5] MBBR reduces the risk of losing annamox biomass.[3] The system includes a patented aeration process. It achieved 85% TN and 95% ammonia reduction in one study.[6]

 [1]CH2M Hill 2017, [2]USEPA 2013, [3]AECOM 2017, [4]Nifong et al 2013, [5]AECOM 2017, [6]Veolia

# *Technology Overview*
# ***Enhanced Biological Phosphorous Removal***

*Typical Nutrient Removal*

| | P |
|---|---|
| **Variable** | **High** |
| 25%[1] to >95% TN removal[1] | 80% to >90% TP removal[2] |

## Overview

This is a biological system configured to remove P from activated sludge via heterotrophic bacteria called P accumulating organisms (PAO), which have high affinity for consuming and storing P. P is released by PAOs in the anaerobic phase before being taken up by the same PAOs in the aerobic phase. P is removed from influent and stored in biomass.

## Common Advantages

- One of the most economical ways to remove P from domestic WW (leading to widespread adoption)
- Less reliant on chemical inputs, and thus lower opex, compared to precipitation
- Lower sludge production than precipitation

## Common Limitations

- Higher capex than precipitation processes
- Influent composition can make operation complex
- Additional P in the digester can lead to increased costs due to struvite formation

*The described nutrient removal, permutation, costs, technologies and technologies providers are not exhaustive.*

## Common Permutations

There are a wide range of EBPR variations detailed elsewhere.[3] The conventional process, Modified Bardenpho ($A^2/O$), is configured with anaerobic/anoxic/aerobic zones. $A^2/O$ and the Johannesburg process are common in Europe.[3] Implemented systems may combine EBPR with filtering or chemical (like PhoStrip) nutrient removal.

## Cost Considerations

Costs vary based on existing infrastructure, land availability, technology selected, facility size, and other factors.

EPA[4] notes achieving <1 mg/L TP—at 81–99% removal efficiency—costs 0.14–98.4 *USD/gpd in capex and 0.04–1.85 *USD/gpd in opex using lagoons and oxidation ditches. At 75–99% removal efficiency using precipitation or a variety of biological processes, along with tertiary filtration, costs are 0.03-22.17 *USD/gpd capex and <0.01-2.33 *USD/gpd opex. In Ohio, lifecycle cost estimates for EBPR systems treating 3-5 mg/L influent P ranged from $200-$1,900 USD/MG for systems with 1–2 mg/L TP effluent target.[5] Capex is significant, with average capex of $2.6M USD for 1-4 MGD facilities and $1.9M for 5–10 MGD facilities.

## Illustrative Technology Variations

The 3-stage Modified Bardenpho ($A^2/O$) process utilizes an anoxic tank for denitrification. The total configuration is of anaerobic-anoxic-oxic phases. The process is beneficial in the removal of both P and N. Two U.S. facilities treating 26 and 57 KLD achieved 2.3-7.0 mg/L TN and <2.3 mg/L TP with this process.[6]
In the Modified Bardenpho (5-Stage process), five phases of treatment include anaerobic, anoxic, and aerobic tanks that remove C, N, and P. Denitrification occurs in the anoxic tank, and minimization of P is realized in the secondary settling. A 1.4 KLD facility in New Jersey achieved 2.6 mg/L TN and 0.09 mg/L TP with this process.[6]



[1]EPA 2 and assuming influent TN of 50 mg/L for Table 2-1 values, [2]Robles et al 2020, [3]HAMK 2018, [4]EPA 1 *(these costs in 2012 dollars) [5]IWMI, [6]Esfahani et al 2019

*Technology Overview*

## *Chemical Precipitation*

*Typical Nutrient Removal*

| N | P |
|---|---|
| **Low** | **High** |
| 0% to 30% ammonium ion reduction[1] | 10% to 90% phosphate ion reduction[1] |

## Overview

Chemicals are added to wastewater to precipitate nutrient-containing salts. Precipitated salts often contain both N and P, but typically P is removed in greater quantities.

## Common Advantages

- High P removal can be achieved
- Marketable product can be recovered
- Reduced maintenance costs associated with unintended struvite formation

## Common Limitations

- Typically cost-negative; recurring chemical costs
- Recovery of P-rich compounds from sludge can be challenging
- P-rich product can be impure
- Operations can be complex & require upstream treatment processes to be effective

*The described nutrient removal, permutation, costs, technologies and technologies providers are not exhaustive.*

## Common Permutations

Aluminum and irons salts are the most widely applied additives[2] and can achieve effluent concentrations of 0.3–0.5 mg/L TP[2]; magnesium salts are the most typical additive for crystallization processes. Chemicals are commonly added to the sludge treatment process or primary clarifier effluent, but many other configurations are possible. Process by-products may include nutrient-rich biosolids or crystalized products like struvite, brushite, or calcium phosphate. Value of by-products varies; some are more effective fertilizers than others.

## Cost Considerations

Not considering O&M savings and revenues, costs ranged from \$6–11 USD/kg of P recovered one study.[1] Lifecycle costs depend on recovered product value, process configuration, O&M savings, and scale. Capex can be high, with one system costing \$2–5M upfront for a 19,000 m3/d facility.[3] By-product prices range from \$110 to up to \$10,000 USD/ton[1]; identifying by-product buyers can add complexity for utilities, although some partnering technology providers reduce this burden.

## Illustrative Technologies and Providers

Providers of commodity salts for P precipitation include ALAR and Hawkins. Additives like alum or ferric salts can be added to wastewater to precipitate P (e.g., ferric ions reacting with phosphate ions to form ferric phosphate). Salts may be added upstream of a filter to precipitate soluble P, increasing the amount eventually removed by the filter.

Providers of struvite crystallization technologies include Centrisys-CNP and Ostara. In Ostara's system, magnesium is combined with P-rich steam in a pH-controlled environment to crystallize a struvite fertilizer.[4] Estimated \$2–5M investment cost.[3] Has been adopted (example) in response to EBPR-related struvite build-up challenges.



[1]Robles et al 2020, [2]HAMK 2018, [3]IWMI, [4]Ostara Pearl® Brochure

*Technology Overview*

# *Sorption Media*

*Typical Nutrient Removal*

| N | P |
|---|---|
| **High**<br>80% to 95% ammonium ion reduction[1] | **High**<br>75% to 90% phosphate ion reduction[4] |

## Overview

Nutrients are attracted (either permanently or reversibly) from liquid to a high-surface area media.

## Common Advantages

- High affinity/specificity for ammonium
- High removal efficiency
- High reaction kinetics can make performance less dependent on retention time[3]
- Simple and low-cost operation

## Common Limitations

- Sorbent fouling over time
- Performance may be pH-dependent
- Performance varies by material; available material may not be ideal
- Regeneration can require caustic materials
- Non-nutrient ions can create challenges

*The described nutrient removal, permutation, costs, technologies and technologies providers are not exhaustive.*

## Common Permutations

Common sorbet medias include natural and synthetic zeolites and clays, polymeric ion exchange (IX) resins, biochar, activated carbon, and agricultural/industrial waste materials.[1] Local availability, cost, ease-of-use, ease-of-disposal, and nutrient removal efficiency differentiate the materials. Spent sorbents are often (but not always) able to be recovered/reactivated after use.[2] IX is a variation of a sorption process wherein target ions (e.g., ammonium, phosphate) are removed from water through exchanging with a benign ion (e.g., chloride, hydroxide).[2] Clinoptilolite (capacity 2–30 mg ammonium/g) and Polonite® (12% P capacity by weight) are promising IX materials for N and P, respectively.

## Cost Considerations

The most common absorbents, natural zeolites and clays, range from $30-120 USD/ton.[1] An EPA study in 1973 estimated that 95.7% ammonia could be removed from 5 mg/L influent at a lifecycle cost (in 2020 dollars)[5] of ~$58/kg ammonia for a~38 KLD facility. Polonite® material costs <$1000 USD/ton[3] but has a higher P capacity; it could cost ~$8.33 USD of sorbent per kg of P recovered.[5]

## Illustrative Technologies and Providers

Adsorptive P medias include Filtralite® and EcoFiltration (Polonite). Polonite is a natural calcium silicate that has been incorporated in filter in over 6,000 treatment facilities.[6] It achieved 91% phosphate removal[7] with capacity of 120 g of P per kg Polonite in one study.

Ammonia IX systems include those from Suez and Wigen. Examples of clinoptiolite suppliers are listed here. An EPA study[5] found the use of clinoptilolite as an ammonia IX material at 38 KLD treatment plants achieved 95.7% ammonia removal at a cost of ~$58/kg ammonia removed.



[1]Huang et al 2017, [2]Pickett et al 2020, [3]Trotochaud et al, [4]Nilsonn et al, [5]EPA and assuming 5.25x inflation from 1974-2020, [6]Ecofiltration, [7]Bunce et al 2018

# Appendix B – Additional Identified Technologies

## Key factors to consider when reviewing

- This **list is a result of RTI's search for innovative algae, membrane-separation, and electrochemical technologies** for removing nutrients from human waste. Search methods included reviewing databases (including for patents and private companies) and peer-reviewed literature as well as engaging with RTI's network.
- RTI did NOT search for or attempt to comprehensively identify technologies using precipitation, adsorption, biological (other than algae), or other approaches to nutrient removal. However, some providers using these technologies are included in the following tables (if they were identified through RTI search methods).
- The **inclusion of providers in the following tables does NOT reflect a characterization by RTI** that the technology is appropriate for all nutrient-removal scenarios. Further research and engagement by the reader will be required to determine if a given technology is appropriate for their application.
- The **exclusion of providers in the following tables does NOT reflect a characterization by RTI** of the nutrient removal technology or provider.

## Definitions of column headers

**Provider (with link):** Providers may be companies, universities, or government agencies that are developing or commercializing nutrient removal technologies. Links may lead to the organization developing or commercializing the technology or related publications (such as peer-reviewed articles or patents).

**HQ:** The country that RTI believes is the primary location of the provider.

**Approach:** The type of technology RTI understands to be used by provider to remove nutrients from wastewater.

| Provider (with link) | HQ | Approach | | |
|---|---|---|---|---|
| | | Algae | Membrane-seperation | Electrochemical |
| Afiltra | Germany | | Y | |
| Algae Systems | USA | Y | | |
| AlgEn | Slovenia | Y | | |
| Amogreentech | Korea | | | Y |
| Anfiro | USA | | Y | |
| Aqua Innovations | USA | Y | Y | |
| Aqwind Solutions | Israel | Y | | |

# Algae, membrane-separation, and electrochemical technologies (I / III)

| Provider (with link) | HQ | Approach: Algae | Approach: Membrane-separation | Approach: Electrochemical |
|---|---|---|---|---|
| Afiltra | Germany | | ■ | |
| Algae Systems | USA | ■ | | |
| AlgEn | Slovenia | ■ | | |
| Amogreentech | Korea | | | ■ |
| Anfiro | USA | | ■ | |
| Aqua Innovations | USA | ■ | ■ | |
| Aqwind Solutions | Israel | ■ | | |
| Ariel University | Israel | ■ | | |
| Beijing Forestry University | China | | | ■ |
| BiO2 Solution | USA | ■ | | ■ |
| Biovantage Resources | USA | ■ | | |
| Birla Institute of Technology | India | | | ■ |
| BLUE-tec | Netherlands | | ■ | |
| Boydel Wastewater Technology | Canada | | | ■ |
| Caltech | USA | | | ■ |
| Cerahelix | USA | | ■ | ■ |
| Chevron USA Inc. | USA | | ■ | |
| CLEARAS Water Recovery | USA | ■ | | |
| Clemson University | USA | | ■ | |
| Current Water Technologies | Canada | | | ■ |
| Department of Energy and Environment | India | | ■ | |
| Desalitech | USA | | ■ | |
| Digested Organics | USA | | ■ | |

# Algae, membrane-separation, and electrochemical technologies (II / III)

| Provider (with link) | HQ | Approach: Algae | Approach: Membrane-separation | Approach: Electrochemical |
|---|---|---|---|---|
| e2metrix | Canada | | | ■ |
| Eawag | Switzerland | | ■ | ■ |
| EcoSTP | India | ■ | | |
| Electro-Chemistry | USA | | | ■ |
| FT Water Solutions | USA | | | ■ |
| Gen3Bio | USA | | | |
| Genesis Water Technologies | USA | | | ■ |
| Global Algae | USA | ■ | | |
| Gross-Wen Technologies | USA | ■ | | |
| Hoganas | Sweden | | | ■ |
| Hydrokemos | Spain | | | ■ |
| Indra Water | India | | | ■ |
| Industrial Phycology | UK | ■ | | |
| Jiangnan University | China | | ■ | |
| LEDCOR Group | USA | | | ■ |
| MicroHAOPs Inc. | USA | | ■ | |
| microTERRA | Mexico | ■ | | |
| Nanyang Technological University | Singapore | | ■ | |
| NASA Ames | USA | ■ | | |
| NewTerra | Canada | | ■ | |
| Ohio University | USA | | | ■ |
| Phycoil Biotech | Korea | ■ | | |
| Princeton University | USA | | | ■ |

# Algae, membrane-separation, and electrochemical technologies (III / III)

| Provider (with link) | HQ | Approach | | |
|---|---|---|---|---|
| | | Algae | Membrane-separation | Electrochemical |
| Saltworks Technologies | USA | | X | |
| Stanford University | USA | | X | |
| Terragon Environmental Technologies | Canada | | | X |
| Triangle Environmental | USA | | X | |
| Tsinghua University | China | | X | |
| UMass Amherst | USA | X | | |
| Universidad de Almeria | Spain | X | | |
| Universitat Politecnica de Catalunya | Spain | X | | |
| University of Queensland | Australia | | | X |
| Waterloo Biofilter Systems | Canada | | | X |
| Weco | France | | | X |
| Wisconsin Alumni Research Foundation | USA | | | X |

## Technologies using other or unidentified approaches (I / II)

| Provider (with link) | HQ | Approach | | | |
|---|---|---|---|---|---|
| | | Adsorption | Precipitation | Biological (non-algae) | Other or not identified |
| Aclarity Water | USA | | | | ■ |
| Again Nutrient Recovery | Sweden | ■ | | | |
| AquaCare | Netherlands | ■ | | | |
| Aquafortus | New Zealand | | | | ■ |
| Atmonia | Iceland | | | | ■ |
| Axine Water | Canada | | | | ■ |
| BioAlchemy | Japan | | | ■ | |
| Biogill | New Zealand | | | ■ | |
| Biokube | Denmark | | | ■ | |
| Bion Environmental Technologies | USA | | ■ | | |
| Biopipe | USA | | | ■ | |
| Biorock (Rotoplas) | Mexico | | | ■ | |
| Centrisys / CNP | USA | | ■ | | |
| Eawag | Switzerland | ■ | | | |
| Frontier Water Systems (Evoqua) | USA | | | ■ | |
| Gen3Bio | USA | | | | ■ |
| Georgia Tech | USA | ■ | | | |
| HSY | Finland | | ■ | | |
| IOTank | USA | | | | ■ |
| MetaMateria Technologies | USA | | | ■ | |
| Microvi | USA | | | ■ | |
| Montanuniversitat Leoben | Austria | ■ | | | |
| Nanostone | USA | | | | ■ |

## Technologies using other or unidentified approaches (II / II)

| Provider (with link) | HQ | Approach | | | |
|---|---|---|---|---|---|
| | | Adsorption | Precipitation | Biological (non-algae) | Other or not identified |
| Nanyang Technological University | Singapore | | | | ■ |
| NASA Kennedy | USA | ■ | | | |
| Nexom | Canada | ■ | | | |
| NuLeaf Tech | USA | | | ■ | |
| NuReSys | Belgium | | ■ | | |
| Orenco | USA | | | ■ | |
| Pharem | Sweden | | | | ■ |
| PHORWater | Spain | | ■ | | |
| Phosphosolutions | USA | | | | ■ |
| Pontic Technology | USA | | | | ■ |
| Powertech | USA | | | | ■ |
| Pulsed Burst | USA | | | ■ | |
| Satelytics | USA | | | | ■ |
| SepticNET | USA | | | ■ | |
| Starfire Energy | USA | | | | ■ |
| University of Michigan | USA | | | | ■ |
| University of Queensland | Australia | ■ | | | |
| USGS | USA | ■ | | | |
| Wase | UK | | | | ■ |
| Water Warriors | USA | ■ | | ■ | |

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