Controlling Nitrogen and Phosphorus in Wastewater

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Nutrient control technologies help maintain healthy water bodies and prevent eutrophication.

Nitrogen and phosphorus are essential nutrients for the growth and metabolism of microbial populations in biological wastewater treatment processes. Nitrogen supports the production of living tissues, while phosphorus supports cell growth. Both of these elements enter domestic wastewater streams as a result of various human activities. If discharged uncontrolled to a confined body of water (*e.g.,* a lake, estuary, or bay), nitrogen and phosphorous can foster eutrophication — the undesirable aquatic growth of algae and other plants that adversely impact the quality and aesthetic of the body of water (Figure 1) *(1)*. To prevent this, an increasing number of states in the U.S. have been implementing stringent effluent discharge regulations for nitrogen and phosphorus.

This article takes an in-depth look at nitrogen and phosphorus — two nutrients that are commonly discharged in wastewater. It examines nutrient control technologies and describes the biochemical reactions involved in treating nutrient-laden wastewater.

▲ **Figure 1.** Eutrophication is the undesirable growth of algae and other aquatic plants that adversely impact bodies of water. Eutrophication from uncontrolled nutrient discharge can be seen in the Long Island Sound *(1)*.

Nutrients in wastewater and their sources

Nitrogen. In domestic sewage, nitrogen is associated with waste materials from various cooked and uncooked foods, including vegetables and meat products. Other major sources are organic nitrogenous compounds (proteins, lipids, etc.) in human and animal wastes. Discharges from chemical fertilizer manufacturing plants and agricultural runoff streams also contribute heavily to the organic nitrogen load in wastewater. A significant portion of these organic nitrogenous compounds is hydrolyzed by natural bacteria into ammonia. The sum of the organic nitrogen and ammonia in a waste stream is called the total Kjeldahl nitrogen.

In wastewater treatment processes, a part of the incoming nitrogen is consumed by biomass for cell growth, another part is oxidized to nitrite and nitrate ions, and the remainder is discharged with the effluent.

Ammonia is present in water as ammonium ions and free ammonia in equilibrium. The distribution of these species is a function of pH and temperature. Removal of ammonia from the discharge of treated effluent is beneficial to the aquatic environment because ammonia is toxic in

high concentrations. It also imposes a high oxygen demand, consuming oxygen that might be necessary to support fish and other forms of aquatic life.

Phosphorus. Domestic wastewater contains phosphorus from foods, vegetables, and human and animal wastes. Laundry waste containing phosphoric detergents is another source of phosphorus in domestic wastewater. Chemical fertilizers in agricultural runoff streams also contribute phosphorus unless they are segregated and handled in separate sewer systems.

The need for nutrient control

The Chesapeake Bay is the largest estuary in the U.S., covering 165,000 km^2 in parts of six states — New York, Pennsylvania, Delaware, Maryland, Virginia, and West Virginia. The bay is fed by 50 tributaries and drains into the Atlantic Ocean. It is a confined structure with a circulation pattern that promotes enrichment of the water body with nutrients. These nutrients foster the growth and proliferation of algal blooms that hinder the penetration of light into the water. When algal cells die and decompose, they release toxic ammonia, which favors biochemical oxidation, imposing a large dissolved oxygen (DO) demand that deprives fish and other aquatic life of oxygen. To mitigate nutrient pollution, the sewage treatment plants (STPs) that discharge treated effluent to the Chesapeake Bay ecosystem are strictly regulated for ammonia, total nitrogen (TN), and total phosphorus (TP).

Likewise, the Great Lakes, which are shared by the U.S. and Canada, contain 20% of the world's fresh water and 84% of the fresh water in the U.S. *(2)*. Agricultural runoff and rapid urbanization contributed to widespread deterioration of the lakes' water quality in the 1960s and 1970s. Extensive studies and mathematical modeling determined that phosphorus — originating from fertilizers in agricultural runoff and from laundry detergents — is the limiting nutrient and main culprit behind the deterioration. The deterioration prompted an effort by both countries to limit the discharge of phosphorus. Regulatory and voluntary control efforts have helped gradually restore the Great Lakes. However, while the point sources have been effectively controlled by a combination of technology and regulatory oversight, distributed sources (*i.e.,* agricultural runoff) are more difficult to control.

Nitrification and denitrification

Nitrogen in wastewater is controlled biologically by a two-step process — nitrification of ammonia (NH_3) to nitrate ions (NO_3^-), followed by denitrification of nitrates to nitrogen gas (N_2).

Step 1. Nitrification. Figure 2 summarizes the biological nitrification of organic nitrogenous compounds. Table 1 delves further into the process of biological nitrification, and lists the biochemical reactions involved in this process.

Table 1. Several biochemical reactions take place during the biological nitrification of organic nitrogenous compounds.

Organic Nitrogen Breakdown	Organic Nitrogen $\longrightarrow$ Ammonia (NH_3, NH_4^+)
Ammonia Equilibrium	$NH_4^+ + OH^- \leftrightarrow NH_3 + H_2O$
Ammonium Oxidation	$NH_4^+ + 1.5\ O_2 \longrightarrow NO_2^- + H_2O + 2\ H^+$
Nitrous Acid Equilibrium	$NO_2^- + H^+ \leftrightarrow HNO_2$
Nitrite Oxidation	$NO_2^- + 0.5\ O_2 \longrightarrow NO_3^-$

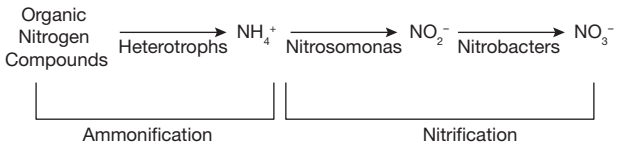
As shown in Figure 2, ammonium (NH_4^+) oxidation is a two-step process. The first step of oxidation to nitrite ions (NO_2^-) is mediated by bacteria called *nitrosomonas*. The nitrite ions are then oxidized to nitrate by bacteria of the genre *nitrobacter*. Both bacteria are autotrophic microorganisms that utilize inorganic carbon (*e.g.,* bicarbonate ions, carbon dioxide) for food and energy. Autotrophic organisms are sensitive to environmental conditions. Some of the important parameters to ensure successful nitrification include:

• *Temperature*. The optimum nitrification temperature range is 15°C to 35°C. The reaction rates slow down significantly when the temperature is below 10°C, and the activity drops when the temperature is above 38°C.

• *Dissolved oxygen (DO)*. It is necessary to maintain a DO level above 2 mg/L for successful nitrification. Nitrification imposes a large oxygen demand. Every gram of ammonia-nitrogen (*i.e.,* every gram of nitrogen contained in ammonia) requires 4.57 g of oxygen, which is supplied by aeration blowers to the reactors through diffusers.

• *pH*. The optimum pH range for nitrification is 6.5–8. Nitrification produces hydrogen ions, creating an acidic condition that needs to be neutralized by adding alkalinity to maintain a stable pH. Alkalinity consumption for nitrification is 7.14 g $CaCO_3$ per gram of ammonium-nitrogen. If the wastewater does not have an adequate buffering capacity, alkalinity has to be added from an external source.

In addition, nitrifying organisms are very sensitive to certain inhibitory and toxic chemicals. Therefore, maintain-



▲ **Figure 2.** The biological nitrification of organic nitrogenous compounds follows this multistep process *(3)*.

ing proper operating conditions is essential for sustaining their population in the wastewater treatment reactor.

The growth rates of autotrophs are orders of magnitude less than those of heterotrophs. Whereas autotrophs consume inorganic sources of carbon for energy and food, heterotrophs consume only organic carbon — mainly plant and animal matter. Biochemical oxygen demand (BOD) is a measure of the amount of dissolved oxygen required for bacteria to degrade (oxidize) the organic components in a water or wastewater system. BOD in wastewater samples is analyzed following a standard procedure *(4)*.

Chemical oxygen demand (COD) is also a measurement of the total amount of organic materials present in water. The difference between BOD and COD is in the analytical method used to determine them. BOD indicates the dissolved oxygen demand to biochemically oxidize organic pollutants in wastewater. COD is determined by chemically oxidizing a sample using Cr (VI) as the oxidant *(4)*. The COD of a sample is higher than its BOD because chemical oxidation is a more agressive process than biochemical oxidation. Note that BOD and COD are both indirect measurements of the amount of carbon in a water sample, and are used interchangeably with the terms "carbon" and "carbon source" throughout the article.

The conversion to nitrite and nitrate does not ensure the complete elimination of nitrogen, as these ions in the effluent still contain nitrogen and serve as nutrients to aquatic plant growth.

Step 2. Denitrification. The denitrification of nitrate to nitrogen gas by carbon oxidation also produces carbon dioxide and water; nitrates serve as the source of oxygen necessary for this step. The bacteria carrying out this reaction are heterotrophic. The main difference is that BOD oxidation and nitrification use aeration, which provides mixing energy and oxygen for respiration, whereas denitrification is an anaerobic reaction, which occurs in the absence of oxygen (and without aeration). Oxidation in anaerobic conditions is called anoxic when nitrate and nitrite ions are the oxygen source. Denitrification reactors are equipped with mechanical mixers for agitation because there is no aeration in anoxic conditions.

The factors that affect denitrification include:

• *Temperature*. The optimum temperature range for denitrification is 15°C to 35°C.

• *DO*. The DO concentration is a critical factor in denitrification, because an increase in DO decreases rates. Therefore, it is essential to incorporate processes, structural designs, and techniques to reduce DO concentration below 0.5 mg/L in anoxic stages.

• *pH*. The ideal pH for denitrification is 7–9; a pH outside of this range may adversely affect denitrification rates.

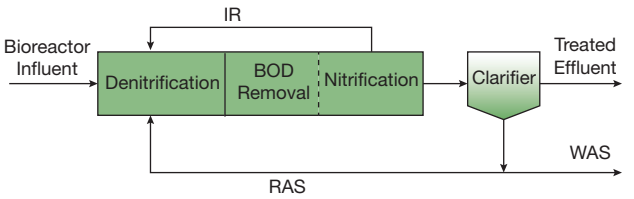
Bacteria involved in denitrification require organic carbon for food and energy. Even though carbon sources are present in the influent, they may be insufficient for denitrification in some cases. Therefore, external carbonaceous feeds like methanol are added. Literature reports a typical ratio of BOD to nitrate-nitrogen of 4:1 to maintain or increase denitrification rates *(5)*.

Nitrogen control in practice

A combination of nitrification and denitrification reactors in series can be used for TN control. The simplest reactor configuration to achieve desired BOD (or COD), TN, and total suspended solids (TSS) levels in the treated effluent is the modified Ludzack Ettinger (MLE) process (Figure 3).

The influent enters the pre-anoxic stage, where denitrification occurs. Then, the mixed liquor (biological solids suspended in wastewater) flows into the aerobic (aerated) compartments, where BOD oxidation and nitrification occurs. To facilitate denitrification, a large part of the mixed liquor that contains nitrate ions is returned in the internal recycle (IR) stream from the nitrification stage and in the return activated sludge (RAS) stream from the clarifier to the pre-anoxic stage. Typically, an IR rate of 2–4 times the influent is applied to achieve maximum denitrification with the carbon available in the raw influent. This can help attain effluent TN levels as low as about 6 mg/L. The term total nitrogen is defined as the total amount of nitrogen contained in all forms of nitrogenous species, *e.g.,* unoxidized ammonium ions, nitrite and nitrate ions, and organic nitrogenous compounds.

The pre-anoxic stage in denitrification reduces wastewater treatment operating costs by oxidizing part of the influent with existing nitrate ions, thus eliminating the need for additional oxygen in the aerobic stage. The saving is equivalent to 2.86 g O_2 per 1 g of nitrate-nitrogen. Another saving arises from eliminating the need to add alkalinity if the wastewater does not have adequate alkalinity. Denitrification produces 3.57 g alkalinity per 1 g of nitrate-nitrogen that is denitrified, which reduces the amount of alkalinity consumed for nitrification by 50%.



▲ **Figure 3.** The modified Ludzack Ettinger (MLE) process train combines nitrification and denitrification reactors in series for total nitrogen (TN) control. Both the return activated sludge (RAS) stream and internal recycle (IR) stream return nitrate ions to the denitrification stage. The nutrient excess is removed in the waste activated sludge (WAS).

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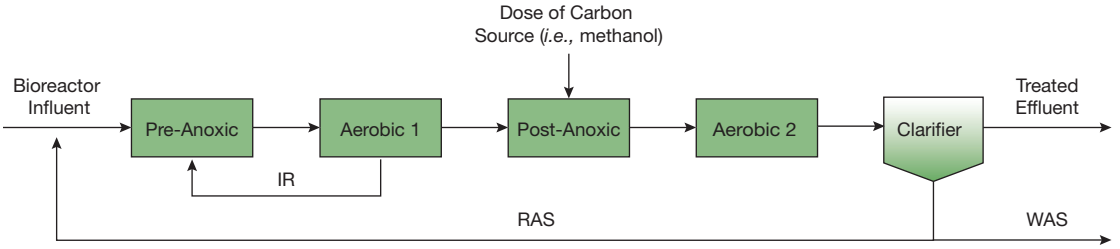


▲ **Figure 4.** The four-stage Bardenpho process has pre-anoxic, aerobic, and post-anoxic stages in series, along with an additional aerobic stage to remove any final traces of carbon. The return activated sludge (RAS) stream and internal recycle (IR) stream help the process meet stringent total nitrogen (TN) limits. The nutrient excess is removed in the waste activated sludge (WAS).

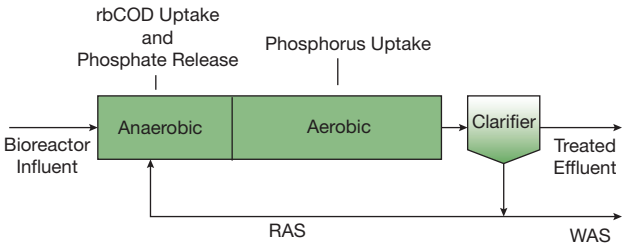
In some jurisdictions, regulations impose stringent TN limits of 5 mg/L or less. In such cases, denitrification in the pre-anoxic stage alone is inadequate and needs supplementation in a post-anoxic stage (Figure 4). This process is referred to as a four-stage Bardenpho process. In this process, mixed liquor from the Aerobic 1 stage is routed through a post-anoxic stage where carbon is supplied in the form of methanol (or, some other easily biodegradable substrate). A limitation of this process is the potential carryover of excess carbon, which may push the final effluent COD above the regulatory limit if the chemical dosing is not controlled closely. To mitigate such a situation, a second aerobic stage (Aerobic 2) is added as a polishing stage to remove final traces of carbon.

Integrated nitrogen and phosphorus removal

Effluent phosphorus limits vary from state to state, typically from 0.1 mg/L to 1 mg/L, although lower limits are being enforced by regulators in some jurisdictions. Many states have implemented a total maximum daily load (TMDL) program that limits nutrient discharge.

Phosphorus can be removed biologically by the enhanced biological phosphorus removal (EBPR) process, by a chemical process, or by a combination process. EBPR consists of two main steps (Figure 5):

1. incorporation of phosphorus in microbial cells in excess of the normal composition of 2%
2. removal of excess phosphorus in the waste activated sludge (WAS).



▲ **Figure 5.** The enhanced biological phosphorus removal (EBPR) process uses phosphorus-accumulating organisms (PAO) in an initial anaerobic stage to biologically remove phosphorus.

The first step is mediated by phosphorus-accumulating organisms (PAO) in the RAS stream in an anaerobic stage at the beginning of the biological treatment sequence. Organic polyphosphates that are stored in the PAO cells are released as orthophosphate (OP) ions in this anaerobic stage. Next, as the mixed liquor enters the aerobic stage, the PAO population increases its phosphorus concentration to approximately 20–30% of the cell dry weight, compared to a normal phosphorus concentration of 1–2%. The released OPs in the anaerobic stage can increase the OP concentration to as high as 40 mg/L, compared to only 5–8 mg/L in the influent *(6)*.

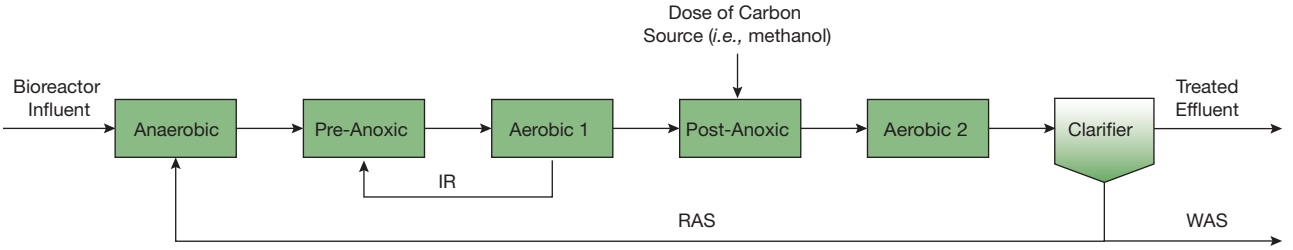
The three biochemical processes that occur in the anaerobic stage are:

1. hydrolysis of particulate and slowly biodegradable organic matter, followed by fermentation into readily biodegradable COD (rbCOD), such as acetate or butyrate
2. uptake of rbCOD and its storage in the form of polyhydroxybutyrate (PHB) within the PAO cells
3. breakdown of polyphosphates in the PAO cells into OP. This step is also releases energy that fuels the uptake of rbCOD in PAO cells.

Theoretically, the ratio of phosphorus release to acetate uptake is between 0.5 and 0.7 *(7)*.

Next, in the aerobic stage, the PAO population in the mixed liquor takes up OP. The energy necessary for this uptake of phosphorus is provided by the breakdown of PHB stored in a second aerobic stage. The aerobic microorganisms consume the broken-down organic products, which are part of the overall BOD.

An integrated biological treatment system, called a five-stage Bardenpho process, is used for applications that require removal of both nitrogen and phosphorus (Figure 6). The treatment system features an initial anaerobic stage for biological phosphorus removal, followed by the conventional four-stage Bardenpho process. If the effluent nitrogen limit is below 6 mg/L, a post-anoxic stage is typically added in series, where a dose of methanol (or another source material for rbCOD) is added to denitrify the remaining nitrate to the desired level. A final polishing aerobic stage removes any residual COD that may form in



▲ **Figure 6.** The five-stage Bardenpho process is, in essence, the four-stage Bardenpho process with an anaerobic stage at the beginning that allows for biological phosphorus removal. The addition of the anaerobic step enables the five-stage process to control both nitrogen and phosphorus. The nutrient excess is removed in the waste activated sludge (WAS).

the event of overdosing of methanol.

PAO are vital to the success of EBPR processes. However, they compete with a microbial population that has similar characteristics and that uses the energy from the breakdown of PHB to pick up glycogen, instead of phosphorus, in the aerobic stage. These are glycogen-accumulating organisms (GAO), and they interfere with the performance of PAO. It is essential to maintain the following environmental conditions that favor PAO growth and prevent competition by GAO:

- a temperature of 5°C–15°C
- a pH between 7 and 7.5
- a COD to phosphorus ratio less than 50
- a DO concentration of 2.5–3 mg/L
- an overall solids retention time (SRT) greater than 3 days
- an anaerobic hydraulic retention time (HRT) of 0.5–1 hr (SRT refers to the time the biomass spends in the total reactor train, whereas HRT is the total time the liquid stream spends in the reactor train)
- an aerobic HRT roughly 3–4 times that of the anaerobic HRT
- an oxidation reduction potential (ORP) of –50 mV to –100 mV in the anaerobic stage and 50 mV to 100 mV in the aerobic stage.

In addition, it is essential to maintain totally anaerobic conditions in the anaerobic stage to eliminate dissolved oxygen and nitrates in the influent and RAS streams.

The BOD or COD of the raw influent provides the necessary carbon that is essential for the success of the EBPR process. Approximately 7–11 g of rbCOD *(8)* or 15–25 g of BOD is required for the uptake of every gram of phosphorus in domestic sewage. In a total biological nutrient removal (BNR) plant that requires both nitrogen and phosphorus control, it is critical to ensure that the raw influent has sufficient carbon to support both TN and TP control.

Influents with low organic content may not contain enough carbon for both EBPR and denitrification. In such cases, acetic acid may be added in the anaerobic stage to compensate for the shortfall. Furthermore, communities may elect to control phosphorus entirely by chemical means instead of biological. In most cases, EBPR is the process of choice with a final polishing by chemical dosing to achieve very low quantities of phosphorus. Also, a backup chemical system is commonly installed in plants that use EBPR to ensure compliance in the event of a failure of the biological system.

Chemical phosphorus control involves dosing hydrated aluminum sulfate ($Al_2(SO_4)_3 \cdot 18\ H_2O$, or alum) or ferric chloride ($FeCl_3$) prior to the secondary clarifier that provides solid-liquid separation. The reactions between aluminum and ferric ions with OP ions are:

$Al^{3+} + PO_4^{3-} \rightarrow AlPO_4(s)\downarrow$

$Fe^{3+} + PO_4^{3-} \rightarrow FePO_4\ (s)\downarrow$

Aluminum phosphate and ferric phosphate are highly insoluble in water and precipitate as solids. The precipitating solutions are dosed in the mixed liquor prior to the secondary clarifier to remove phosphorus as a sludge with WAS.

Recent developments in nutrient control

Aside from the aforementioned processes, other unconventional processes have gained popularity in recent years to address new demands, namely:

- an increasing need to recycle and reuse treated wastewater globally
- the need to treat increasing volumes of wastewater as the world's population continues to grow
- the need to upgrade existing plants within the given footprint to accommodate increased flows and to comply with increasingly stricter regulations that require low nutrient levels in treated effluent.

Membrane bioreactor (MBR). The MBR is a special application of the suspended-growth process. It produces high-quality, recyclable effluent for potable water and industrial applications. The MBR also helps in significantly reducing the footprint of treatment plants by maintaining a high mixed-liquor suspended solids (MLSS) concentration in the range of 6,000–8,000 mg/L (compared to 2,500–4,000 mg/L in a conventional activated sludge reactor). This is a major advantage as space becomes a limiting factor in siting new plants and upgrading existing ones.

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A basic MBR system consists of an activated sludge reactor that operates at a high MLSS concentration followed by an ultrafiltration (UF) membrane system (Figure 7). The membrane module separates the solids and liquids, replacing the clarifier of a conventional activated sludge process. The permeate is almost completely free of bacteria and viruses. Thus, the MBR effluent requires little additional disinfection, if any. Nutrient control can be achieved by the MLE, four-stage Bardenpho, or five-stage Bardenpho process, as desired.

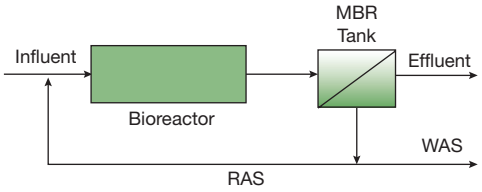
Typically, the membrane module of MBR concentrates the MLSS to 8,000–12,000 mg/L. Some of the thickened stream is wasted as WAS, but the remaining solids are recycled as RAS at four times the influent rate to the bioreactor. This continuously flushes the membrane surface and provides sufficient biomass to sustain a high MLSS.

An MBR system is not required for all reuse applications. Effluent BOD and TSS levels below 10 mg/L are sufficient for applications that do not require the high-quality water produced by an MBR, such as irrigation. However, there has been a steady growth in demand for high-quality treated effluent and therefore MBR processes throughout the world.

Moving-bed bioreactors (MBBR). The MBBR is a media-based fixed-film process in which biomass grows on the surfaces of high-density polyethylene (HDPE) media that is suspended and continuously in motion in the bioreactor. The resulting turbulence helps MBBRs overcome the diffusion limitations to oxygen and substrate (food) transfer that affect fixed-film processes. The biomass attached on the media surfaces carries out the treatment reactions.

The fixed film on media surfaces provides a home for a large population of biomass in limited volume. The biomass on the media surfaces is equivalent to 1,000–5,000 mg/L as suspended solids, but its effectiveness in carbon reduction and nitrification is far greater than that of a suspended-growth reactor of equal volume with comparable MLSS concentrations *(9)*.

BOD oxidation and nitrification occur in different MBBR reactors in series, each of which contains a unique microbial population. Unlike in suspended-growth reactors, the possibility of biomass washout and process failure from toxic or shock loads and/or hydraulic overloading is minimal. Even if such events do destroy some outer layers of the attached biomass, there will still be a sufficient population left in the inner layers to provide the seed for regrowth after the disruptive events. Moreover, because the biomass is attached, there is no possibility of sludge bulking — a situation very common in suspended-growth reactors where sludge fails to separate out in sedimentation tanks.



▲ **Figure 7.** A basic membrane bioreactor (MBR) system consists of an activated sludge reactor that feeds an ultrafiltration (UF) membrane. The UF membrane discharges an effluent that is almost completely free of BOD and suspended solids.

The MBBR is a once-through process that produces waste sludge and does not return a biomass stream to the reactor. However, in treatment processes that require denitrification, an IR stream is returned from the nitrification stage to the pre-anoxic stage. If it is necessary to achieve very low levels of TN, a post-anoxic stage will also be required to support additional denitrification. Supplemental carbon is added externally in these cases.

If necessary, a tertiary filter can be added to render the effluent suitable for reuse. It can be a simple multimedia or UF filter, depending on the reuse application and the desired effluent TSS.

Air is provided to the MBBR reactor for respiration and mixing. The aeration system consists of air blowers and coarse-bubble diffusers that create bubbles to keep the media continuously in suspension. The media (specific gravity of 0.95–0.98) occupies 30–60% of the empty tank volume and floats in water under quiescent conditions. The media is resistant to any degradation by ultraviolet (UV) light.

Integrated fixed-film activated sludge (IFAS) process. The IFAS process is a hybrid between suspended-growth and fixed-film processes. The main difference between the MBBR and IFAS is that the IFAS process has a RAS stream, whereas the MBBR does not.

The IFAS process requires even less reactor volume, media volume, and footprint area than an MBBR for the same level of treatment. The IFAS process is particularly well suited for municipalities that need to increase treatment capacity to serve a growing population or to comply with a regulatory change.

In many cases, existing activated sludge plants can be easily retrofitted to IFAS by adding media, avoiding the need to increase reactor volume and the accompanying significant capital cost. Even in situations where capital expenditure is not the major issue, available space can be a roadblock to the expansion of many older facilities. This obstacle can be overcome by converting an existing activated sludge plant to IFAS. Adding media to grow fixed film and increasing the biomass population in a conventional activated sludge reactor can effectively increase the MLSS of the reactor by 150–200% *(8)*.

In summary, the advantages of MBBR and IFAS over

other types of processes include:

• suitability for treating high flows and loads and for addressing nutrient control requirements within a limited available footprint

• resilience to toxic and shock loads

• minimal capital investment requirements for upgrades.

Partial nitritation/anammox (P/NA) process. Nitrification-denitrification is an expensive process for nitrogen control from both capital and operations viewpoints. The P/NA process, however, can reduce operating costs for aeration and carbon. The two-step P/NA process starts with the aerobic oxidation of ammonia to nitrite by autotrophs, followed by the anaerobic reaction of nitrite with ammonia to nitrogen gas and nitrate. The nitrite that is formed in the first step is suppressed from being oxidized further to nitrate and preferentially reacts with ammonia under the following reaction conditions:

• a high ammonia concentration (above 300 mg/L)

• a low COD to ammonia-nitrogen ratio (1 or lower)

• a high reaction temperature (30–40°C)

• a pH of 6.8–8.2

• anaerobic oxidation (with no DO) in the second (anammox) step.

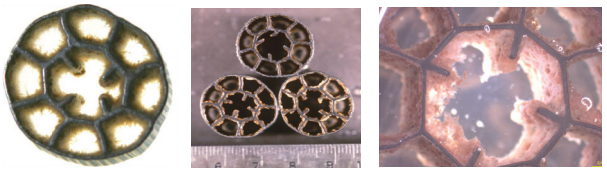
Figure 8 shows photographs of bacteria for BOD oxidation, nitrification, and anammox processes *(10)*.

Anammox is ideal for anaerobic sludge digester return streams, which impose a large ammonia load and oxygen demand on the overall treatment process. Mainstream P/NA (which discharges treated effluent directly to a body of water) is much less common than the sidestream process (which returns treated effluent to the treatment train) because ammonia is much lower in concentration and the operating temperature is much lower than the optimum range of 35–40°C. For perspective, there are about 200 sidestream plants and two mainstream anammox plants in operation globally. Many laboratory, pilot, and full-scale studies are ongoing to characterize and develop this process.

Closing thoughts

The uncontrolled discharge of nitrogen and phosphorus is a major source of pollution of water bodies, but nutrient control technologies are advancing rapidly as innovative and economic solutions are under development.

However, facilities have very little incentive to implement such measures without regulatory drivers. A combined effort by society, regulatory bodies, and industry is necessary to curb pollution of precious bodies by these nutrients. Along with the regulators, the chemical and fertilizer industries that discharge nitrogen- and phosphorus-containing compounds into water also have a role to play in this effort. CEP



▲ **Figure 8.** The growth of bacteria is visible on reactor media in moving-bed bioreactors (MBBR). The photos (from left to right) depict bacteria for BOD oxidation, nitrification, and anammox processes. Images courtesy of Headworks International.

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