Tertiary Denitrification Processes for Low Nitrogen and Phosphorus

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The 2010 *Tertiary Denitrification Processes for Low Nitrogen and Phosphorus Compendium* was written to identify knowledge gaps to be addressed by the Nutrient Removal Challenge. That document contains state-of-the-art knowledge to achieve reliable, cost-effective nutrient removal. The 2010 compendium included a number of questions and challenges to reduce nutrients in advanced treated wastewater. This 2019 compendium revision contains a summary of the findings presented in reports and documents generated by the Nutrient Removal Challenge researchers and contributors.

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●●●● OVERVIEW

This compendium focuses on tertiary denitrification processes and specific issues relating to their design and operation to meet low effluent total nitrogen (TN; <3 mg N/L) and total phosphorus (TP; <0.1 mg P/L) limits. Tertiary denitrification processes are biological processes. They are heavily dependent on upstream nutrient removal performance to ensure appropriate feed conditions. For example, tertiary denitrification filtration requires adequate phosphorus levels for biological growth within the tertiary process coupled with fully nitrified tertiary treatment feed. Tertiary denitrification is typically the last treatment barrier prior to disinfection/discharge in meeting low effluent TN levels (<3 mg N/L). To ensure meeting such levels, operators must supply a supplemental external carbon feed (e.g., methanol) to the tertiary denitrification process because all available readily biodegradable organics have been removed during upstream activated sludge treatment.

The objectives of this compendium are as follows:

- Provide background and discussion on tertiary denitrification technologies
- Give details on tertiary denitrification nutrient requirements to achieve both low effluent TN and TP
- Discuss operational issues of tertiary denitrification technologies that can enhance removal efficiency
- Discuss external carbon source types and dosing issues
- Provide information on what low TN and TP values can reliably be achieved for the listed groups of tertiary denitrification technologies

Several treatment technologies can be used to perform tertiary denitrification. Three groupings of technologies were considered in accordance to the groupings developed in Manual of Practice No. 8 (MOP-8) (WEF 2009):

- Biologically Active Filters (BAFs)—most common
- Moving Bed Biofilm Reactors (MBBRs)
- Fluidized Bed Biofilm Reactors (FBBRs)

Several key features distinguish the different tertiary denitrification technologies. BAFs are the broadest of the three groups and include all denitrification sand filters and post-denitrification biological filters. MBBRs and FBBRs are grouped independently from BAFs because they are not backwashed and have no filtering capability. MBBRs involve biofilm growth on a plastic media carrier with flow through the reactor in a horizontal direction, whereas FBBRs involve biofilm growth on fluidized sand or other ballast particles with vertical flow through the reactor. The operational strategies for each technology vary considerably as a result of inherent differences in their design and configuration.

●●●●● BACKGROUND

This section provides background on nutrient removal in water resource recovery facilities (WRRFs). A subsection is devoted to processes upstream of tertiary denitrification and the parameters impacting the ability to deliver a fully nitrified stream to the tertiary denitrification stage.

Biological Nutrient Removal Background

The removal of nitrogen from WRRFs is primarily achieved by (a) assimilation of nitrogen into biomass and (b) biochemical oxidation/reduction processes that convert organic nitrogen and ammonia to nitrogen gas through a two-step process. The two-step process is commonly referred to as nitrification and denitrification, whereby nitrification entails the oxidation of ammonia to nitrate by nitrifying organisms and then denitrified of nitrate to nitrogen gas by denitrifying organisms. Ammonia oxidation is written as follows (excluding growth requirements):

$$\text{Equation 1: } NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$$
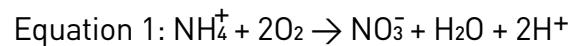
Denitrification (nitrate reduction) can be written as shown below using methanol as an external carbon source (excluding growth requirements):

$$\text{Equation 2: } 6NO_3^- + 5CH_3OH + CO_2 \rightarrow 3N_{2(g)} + 6HCO_3^- + 7H_2O$$
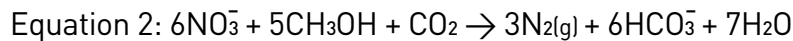
Combined nitrification and denitrification configurations used in activated sludge processes may be capable of achieving low effluent nitrogen concentrations (TN < 3 mg N/L). Tertiary denitrification systems may also be used to achieve similar low effluent total nitrogen concentrations. The reader is referred to other Nutrient Challenge documents covering nutrient removal performance of various technologies and process configurations (Bott and Parker 2011, WRF 2019). A more detailed discussion on nitrification/denitrification, as well as the various activated sludge configurations to perform biological nitrogen removal can be found in the WEF Nutrient Removal MOP-34 (2011a).

Phosphorous can be removed from wastewaters by biological and/or chemical/physical means. Biological phosphorous removal methods involve (a) assimilation of phosphorous (macro-nutrient) into cellular mass and (b) enhanced biological phosphorus removal (EBPR) through the selection and growth of phosphorus-accumulating organisms (PAOs). A more detailed discussion on biological phosphorus removal and EBPR process configurations can be found in the WEF Nutrient Removal MOP-34 (2011a).

In addition to biological P removal, chemical precipitation using a metal salt, such as alum or ferric, is used to reliably meet low effluent TP levels (TP <0.1 mg P/L). Chemical addition will precipitate inorganic phosphorus. The extent of phosphorus precipitation is largely governed by pH, alkalinity,

and the metal dose to orthophosphate ratio. The appropriate pH operating range is based on the coagulant used, whereby alum has a tighter operating range than ferric. Recent work has shown that the metal/phosphorus chemistry is closely tied to hydroxide formation and that covalent bonding to metal hydroxides form the major mechanism for phosphorus removal. Fundamental mechanisms of chemical phosphorus removal (Smith et al. 2008) and process configurations to achieve low effluent TP concentrations were addressed by the Nutrient Removal Challenge (Bott and Parker 2011, WRF 2019a, 2019b).

Delivering a Fully Nitrified Feed to the Tertiary Denitrification Process

It is imperative to supply a fully nitrified feed to the tertiary process. Otherwise, the ammonia will likely bleed through the tertiary denitrification process and unable to meet the TN effluent target objectives. If the upstream process performing nitrification is activated sludge, the following parameters are important for full nitrification:

- Alkalinity
- Aerobic Conditions
- Aerobic Solids Residence Time (SRT)

The nitrification process of converting ammonia to nitrate consumes 7.1 lb alkalinity (as $CaCO_3$) per lb of ammonia as nitrogen nitrified (WEF 2009). This alkalinity consumption may cause inadequate alkalinity concentrations to maintain a favorable pH. Nitrification rates slow considerably at pH values below 6.5 (Suzuki et al. 1974). The rate at pH 6.5 is estimated to be 68 percent of that at pH 7.2 and only 10-20 percent at pH 5.8-6.0 (EPA 1993). Thus, external supplemental alkalinity may be required. The denitrification process adds 3.6 lb alkalinity (as $CaCO_3$) per lb of nitrate-nitrogen denitrified (WEF 2009). However, tertiary denitrification processes do not typically return the recovered alkalinity to the upstream nitrification process.

Nitrifying organisms are obligate aerobes and thus require aerobic conditions to grow. Ensuring adequate dissolved oxygen (DO) levels (>1 mg/L) in the aeration basin ensures aerobic conditions. Maintaining an ample nitrifying biomass inventory is achieved by having a long enough aerobic SRT for sufficient nitrifier growth with full nitrification. Nitrifier growth rate and thus target aerobic SRT is affected by temperature, DO concentration, pH, and other factors such as the presence of inhibitory compounds. A fully nitrifying secondary process should be able to reliably achieve ammonia discharge at 0.5 mg NH_3-N/L or less.

Tertiary Denitrification

This compendium will not cover every tertiary denitrification technology since technologies are constantly evolving. Rather, the focus is on the three primary technology groupings (BAFs, MBBRs,

and FBBRs) as introduced above and previously developed in MOP-8 (WEF 2009). Figure 1 shows an example tertiary denitrification process using a MBBR with downstream filtration. BAFs, MBBRs, and FBBRs operate differently, which results in varying operational considerations for each group.

Figure 1 – Tertiary Denitrification Process Example: Moving Bed Biofilm with Downstream Filtration
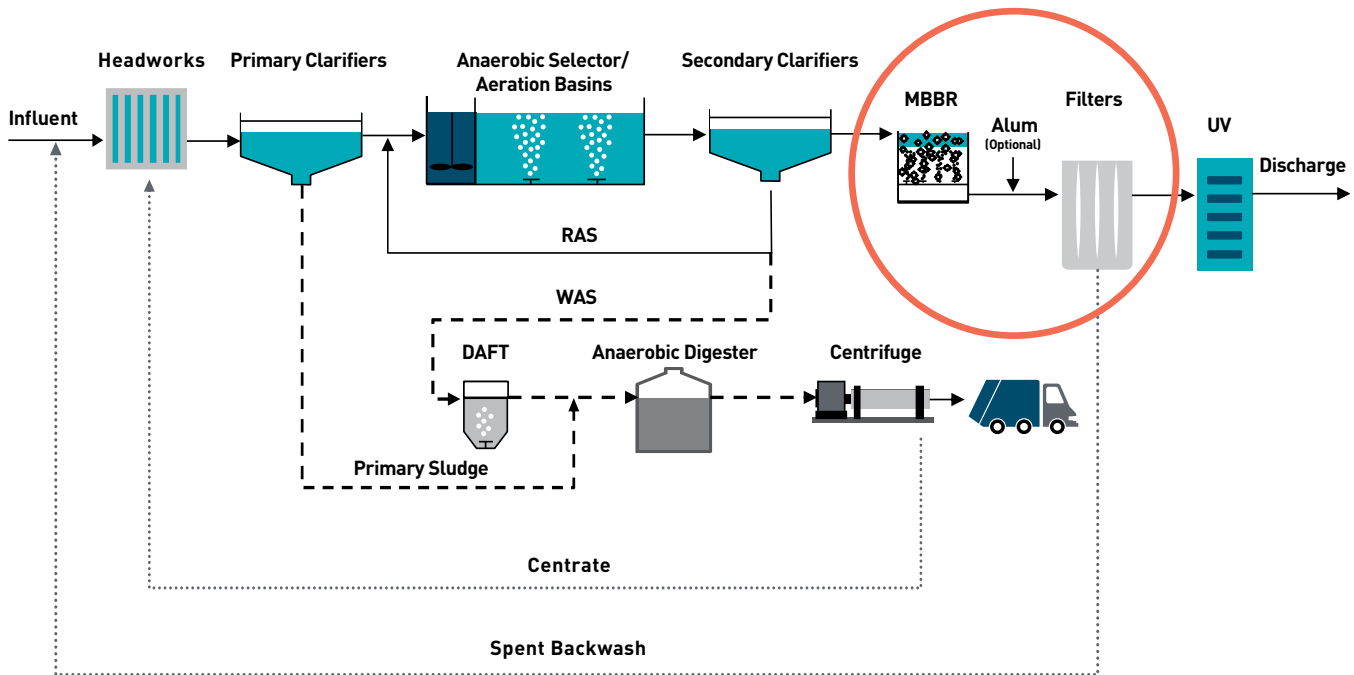
Although this compendium focuses on their use for tertiary denitrification, BAFs, MBBRs, and FBBRs can also be used for nitrification with different design and environmental conditions to sustain the nitrification process. This provides a sequence of tertiary nitrification followed by tertiary denitrification to remove ammonia and nitrate.

Attached Growth Systems

The tertiary denitrification technologies discussed in the compendium are attached growth systems that rely upon a biomass growth on a carrier media. The microbes attach to a surface to form a biofilm. A biofilm is a collection of microbes that attach themselves to a surface bound by extracellular products (Marshall 1984). Attached growth systems enable higher biomass concentrations than suspended growth systems, such as conventional activated sludge. Higher biomass concentrations allow potential for higher volumetric removal rates than suspended growth systems. Attached solids are maintained in the biological basin until a portion of solids detach from the biofilm in a process referred to as sloughing. Sloughed solids are removed from the bulk liquid by clarification, filtration, or other means to achieve low TN and TSS concentrations.

Biofilm Process Modeling

Attached growth biofilm systems are more complex from a mathematical modeling perspective than suspended growth systems. Biofilm thickness, architecture, and composition play an integral part in nutrient and substrate transfer to biomass. Biofilm models mathematically describe biofilm growth coupled with the mass transfer of substrate into biofilms (e.g., Sáez and Rittmann 1992). Model prediction uncertainty persists because of the number of variables (Eberl et al. 2006).

For tertiary denitrification biofilm systems, Harremoës (1976) found that denitrification filter kinetics is limited by NOx-N/COD diffusion into biofilm pores. The gross kinetics are assumed to be zero-order. This notion was tested by the likes of Hultman et al. (1994) and Janning et al. (1995), who revealed a reasonable correlation between observed values and the half-order kinetic model.

Various commercially available wastewater process simulators include elements that can be directly used or manipulated to model BAF, FBBR, or MBBR tertiary denitrification reactors. The model formulation and potential limitations of biofilm models in these simulators must be understood by the engineer to appropriately use such models for design purposes. Prudent design practice relies not only on process simulators but also empirical design guidelines and preferably pilot or demonstration studies to inform design of tertiary denitrification processes to meet low TN limits.

Media Selection

The media selection in tertiary denitrification technologies is predominantly based on biomass growth and head loss. Media with a higher surface area to volume ratio (specific surface area) allows more surface area for biofilm growth and mass transfer and thus a) higher biomass concentrations and removal rates for a given volume and b) greater surface area for mass transfer resulting in thinner biofilms with higher apparent kinetics due to reduced diffusion distances under otherwise equivalent conditions. In the case of BAFs, increased head loss through the filter media and more frequent backwashing are tradeoffs of using media with higher specific surface area.

Tertiary Denitrification Loading

The unit sizing for all the tertiary denitrification technologies is governed either hydraulically or kinetically by NOx-N loading rates. For facilities with no upstream denitrification, sizing of tertiary denitrification technologies are typically kinetically limited by NOx removal. However, most facilities implementing tertiary denitrification to meet low effluent TN and TP concentrations are equipped with nitrogen removal upstream (typically activated sludge). Thus, the unit NOx loading to the tertiary denitrification process is reduced while the hydraulic loading is maintained. Under this situation, sizing will most likely be dictated by the hydraulic loading rate.

●●●● TERTIARY DENITRIFICATION TECHNOLOGIES

This section summarizes BAF, MBBR, and FBBR tertiary denitrification technologies.

## Background on Biologically Active Filters (BAFs)

BAFs encompass a broad group of filter types. During the development of MOP-8 (WEF 2009), the authors reached a consensus that the biological active filter listing will include both the units historically referred to as a biological aerated filter plus traditional denitrification filters. The rationale behind combining the two relates to the fact that both are biologically active and they fall under the category of filtration.

The BAF technology is a submerged compact biological filter (Le Tallec et al. 1999). For all BAF units, the filter media serves two primary purposes: 1) a carrier material supporting biomass growth, and 2) a filtration medium to remove a portion of solids from the liquid stream. Over time, solids build up within the filters and head loss across the filter increases. Periodic backwashing removes accumulated solids and returns the filter to baseline head loss conditions. Based on the grouping developed in MOP-8 (WEF 2009), BAFs are characterized according to their media configuration and flow regime as follows:

- **Downflow BAF with Media Heavier than Water.** This general category includes packed-bed tertiary denitrification reactors, such as Tetra Denite® filters. These BAFs are back-washed using an intermittent counter-current flow regime. They are typically designed to produce filter quality effluent (<5 NTU).
- **Upflow BAF with Media Heavier than Water.** This includes BAFs that use expanded clay and other mineral media, such as Degremont Biofor®. These BAFs are backwashed using an intermittent concurrent flow regime. A schematic of this configuration is provided in Figure 2. These are typically designed as a biological treatment process that also removes suspended solids to secondary concentrations but not to filter-quality effluent.
- **BAF with Floating Media.** This includes BAF with polystyrene, polypropylene, or polyethylene media, such as Kruger Biostyr®. These BAFs are backwashed using an intermittent counter-current flow regime. These are typically designed as a biological treatment process that also removes suspended solids to secondary concentrations but not to filter-quality effluent.
- **Continuous Backwashing Moving Bed Filters.** These filters operate in an upflow mode and consist of media heavier than water that continuously moves downward, countercurrent to the wastewater flow. Media is directed continuously to a center air lift where it is scoured, rinsed, and returned to the top of the media bed. Some well-known filter names are DynaSand®, AstraSand®, and Centraflo®. They are typically designed to produce filter quality effluent (<5 NTU).

- **Nonbackwashing, Submerged Filters.** These processes consist of submerged, static media and are often referred to as submerged aerated filters (SAF) although there has been recent work in applying this technology with anoxic conditions for denitrification. Solids are intended to be carried through the reactor and removed through a separate, dedicated solids separation process.

Figure 2 - Upflow BAF with Media Heavier than Water from a Pilot (A) and a Flow Schematic (B)

A.   **B.**
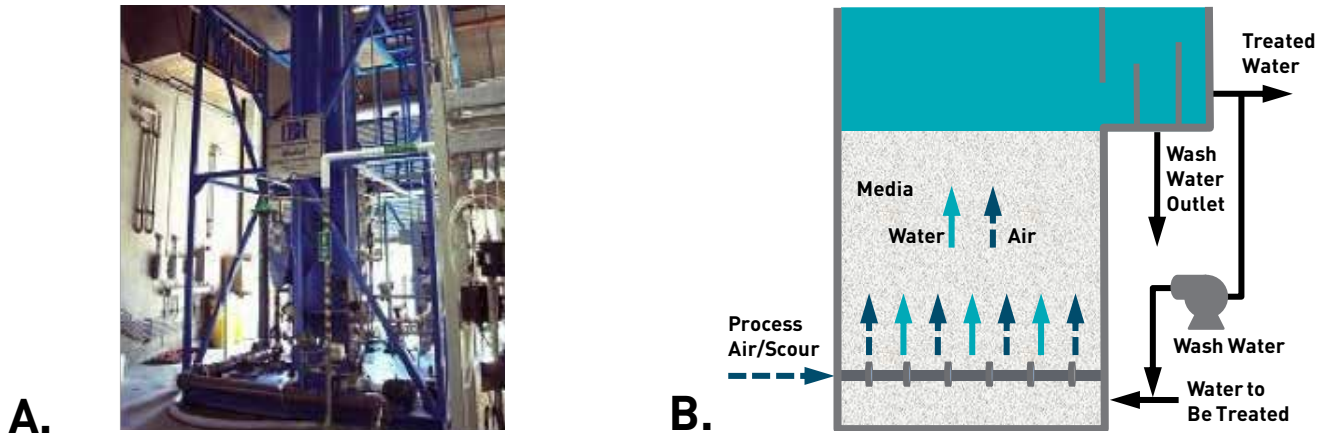
The wide range of BAF configurations results in highly variable, technology-specific, NOx and hydraulic loading rate design criteria. Typical BAF volumetric and hydraulic loading rates are listed in in Table 1. The original denitrification filter design curves were based on denitrification removal rates with respect to empty-bed detention time (Savage 1983). Data from pilot and full-scale systems superimposed onto existing curves suggested that 90 percent NOx removal can be achieved at a hydraulic residence time of 10 minutes and at temperatures ranging from 13°C to 21°C (deBarbadillo et al. 2005). The loading rates range for upflow post-denitrification BAF reactors tends to be higher than for post-denitrification sand filters because they are not designed for the same level of TSS removal and less restricted by hydraulic limitations.

Table 1 - Typical BAF Loading Rates for Tertiary Denitrification

Technology	Applied NOx-N Loading, kg/m³-d (lb/d/1000 cf)	Hydraulic Loading Rate, m³/m²-h (gpm/sf)	NOx-N Removal Efficiency %	Reference
Downflow BAF with Media Heavier than Water	0.3–3.2 (20–200)	Ave.: 4.8–8.4 (2–3.5) Peak: 12–18 (5–7.5)	75–95	Severn Trent 2004, EPA 1993
Upflow BAF with Media Heavier than Water	0.8–5 (50–300)	10–35 (4–14)	75–95	Degremont 2007
BAF with Floating Media	2 (125)			German Assoc. for Water, Wastewater and Waste 1997
Continuous Backwashing Filters	1.2–1.5 (75–94)			German Assoc. for Water, Wastewater and Waste 1997
Nonbackwashing Submerged Filters	0.3–2 (20–120)	Ave.: 4.8–5.6 (2–4) Peak: 13.4 (6)	75–95	deBarbadillo et al. 2005

Source: WEF 2011b

Table 2 - Summary of BAF Backwashing Requirements

| Technology	Backwash Rate, m/h (gpm/sf)	Air Scour Rate, m/h (scfm/sf)	Total Duration (min/day ᵃ)	Total Backwash Water Volume m³/m²/d (gal/sf/d)	Total Backwash Water Volume m³/m²/d (gal/sf/d)
Upflow BAF with Media Heavier than Water Normal BW	20 (8.2)	97 (5.3)	10	3.3 (82)	4.4 (107)
Upflow BAF with Media Heavier than Water Energetic BW (c)	30 (12.3)	97 (5.3)	7	3.5 (86)	3.8 (93)
BAF with Floating Media Normal BW	55 (22.5)	12 (0.7)	16	2.5 (19) (d)	2.5 (19) (d)
BAF with Floating Media Mini-BW (e)	55 (22.5)	12 (0.7)	5	1.5 (11) (d)	1.5 (11) (d)
Downflow BAF with Media Heavier than Water	15 (6)	90 (5)	20-25	5–6 (120–150)	5–6 (120–150)
Continuous Backwashing Filters	0.5–0.6 (0.20–0.24)	Continuous Through Air Lift	Continuous	12–14 (288–346)	12–14 (288–346)

Notes:
a. Backwash duration reflects total duration of the typical backwash cycle, which includes valve cycle time and pumping and non-pumping steps. The duration of each step is adjustable via programmable logic controller and supervisory control and data acquisition control systems.
b. The total backwash wastewater volume includes drain and filter to waste steps where applicable.
c. Energetic backwash once every one to two months depending on trend in "clean bed" head loss following normal backwash.
d. Units as m3/m3/d (gal/cf/d). Backwash volume requirements are based on media volume rather than cell area because depths vary.
e. Mini-backwash applied as interim measure when pollutant load exceeds design load.

Source: WEF 2011b

Background on Moving Bed Biofilm Reactors

A moving bed biofilm reactor (MBBR) is a biological treatment process that uses a basin filled with carrier media that promotes the attachment and growth of biofilm that carries out the biological treatment. A schematic of an MBBR for either secondary or tertiary treatment is shown in Figure 3. MBBR units can be used as a secondary or tertiary process. MBBRs have widespread usage in Europe that date back approximately twenty years with particular emphasis in Norway and other parts of Scandinavia (Ødegaard et al. 2006).

Figure 3 - MBBR Technology (A) Schematic Using Loose Media and (B) Media Image
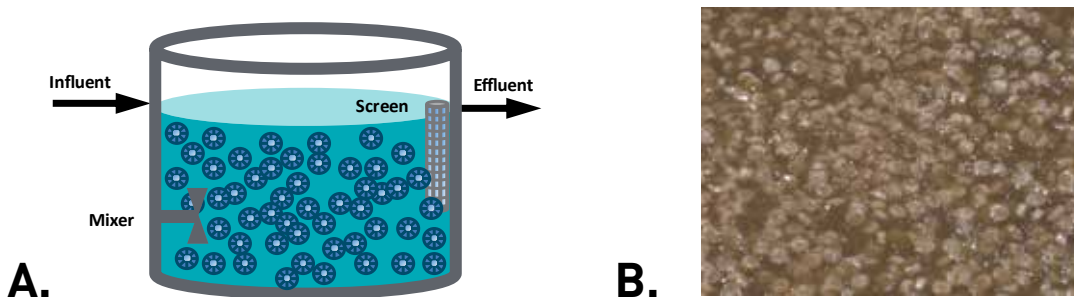
The carrier media is either in a fixed form as sheets/rope or as a buoyant loose plastic media as shown in Figure 4. Maintaining suspension of buoyant loose media requires energy in the form of either aeration or mixing. In the case of tertiary denitrification, the MBBR operates under anoxic conditions with mechanical mixing to maintaining media in suspension and provide hydraulic shear forces to slough excess biomass. Examples of carrier material include the following:

- Rope
- Sponge
- Plastic Pellets
- Trickling Filter Media
- Flat Sheets

The most common form of media is the buoyant loose plastic media, which has shown durability by not requiring replacement in the first generation MBBRs built over 15 years ago (Rusten et al. 2006).

Figure 4 – MBBR Fixed Sheets: Frayed Rope (A) and Plastic Loose Suspended Media (B)

A.

B.
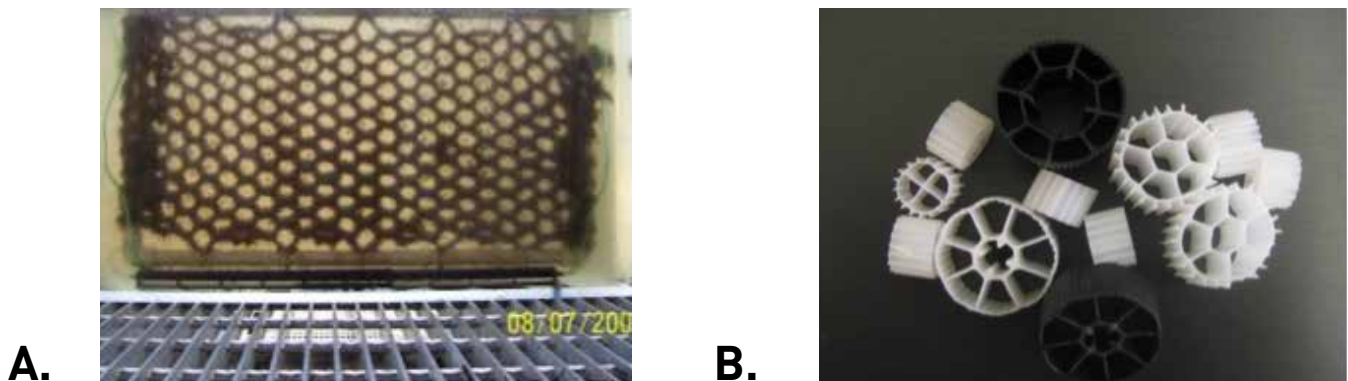
The MBBR process provides a longer SRT by increasing the biomass concentration in the biological basin due to high surface area provided by carrier media without overloading the downstream clarification process. Thus, it requires a smaller footprint than a comparable suspended growth system. Additionally, higher biomass concentrations translate to a potentially more reliable process, especially in colder climates.

The primary difference between a BAF and MBBR is that an MBBR neither provides filtration nor requires backwashing. MBBRs may require a downstream liquid-solids separation process to remove solids produced in the reactor. To meet low TN limits, a downstream solids separation step may be required. A few downstream separation technologies that have been used includes sedimentation (McGettigan et al. 2009), flotation (Helness et al. 2005), filtration (Stinson et al. 2009),

high rate clarifiers (LaFond et al. 2009), and membranes (Melin et al. 2005). Despite having a separation process downstream to remove biomass, the solids are not returned to the MBBR process as in activated sludge. Attached growth processes with solids return the biological process exist and are referred to as integrated fixed-film activated sludge (IFAS).

MBBRs have been used for municipal wastewater treatment applications in Europe for decades as well as in North America to a lesser extent. There are approximately 12 MBBR facilities currently in operation in North America. Pilot data obtained from Norman M. Cole Jr. Pollution Control Plant (NCPCP), Virginia, and Blue Plains Advanced Wastewater Treatment Plant (AWTF), Washington D.C., are summarized and contrasted against three separate full-scale facilities in Table 3. Pilot studies determined that tertiary denitrifying MBBR achieved effluent NOx-N below 2 mg N/L and TP below 1 mg P/L under a range of operating conditions. The data from Täljemark et al. (2004) only shows the effluent total nitrogen concentration, whereas the bottom three rows of Table 3 reveal that NOx-N effluent concentrations can meet levels of less than 2 mg N/L.

Table 3 - Typical MBBR Loading Rates for Tertiary Denitrification							
Applied NOx-N Loading g N/m2/d (lb N/sf/d)	Flow, m3/d (mgd)	Media Fill %	NOx-N Removal Rate g N/m2/d (lb/sf/d)	Effluent TN-N mg N/L	Effluent TP mg P/L	Downstream Clarification	Reference
1.2 (0.25)	126,000 (33)	50	1.05 (0.21)	6.8[a]	0.21	DAF	Täljemark et al. 2004
1.2 (0.25)	23,800 (6)	36	1.05 (0.21)	5.8[b]	0.15	Filtration	Täljemark et al. 2004
0.45 (0.09)	8.700 (2.3)	23		<1 [a,c]	<1	Filtration	Wilson et al. 2008
1.6 (0.33)	6.7 [d]	30		< 2 [a,c]	—	Filtration	Pilot Testing, Washington, D.C. (Stinson et al. 2009)
1.4-2.5 (0.29-0.51)	—	40		< 1 [a,c]	< 0.17	Filtration	Pilot Testing, NCPCP, VA (McGettigan et al. 2009)

Notes:
a. Methanol used as external carbon source
b. Ethanol used as external carbon source
c. Effluent NOx-N
d. Gallons per minute

Source: WEF 2011b

MBBR Specific Design Considerations

The fill fraction, or ratio of bulk media volume to reactor volume, can vary depending in the media type. With fixed media, designers pack in as many modular racks as possible without compromising basin hydraulics. With loose media, fill percentage may range from 30 percent (McGettigan et al. 2009) to 67 percent (Hem et al. 1994). Loose media is prone to "migrating" along the flow path resulting in an uneven distribution in the basin. Loose media may be pushed into a corner of the basin, thereby reducing contact between NOx-N and the biofilm and thus treatment efficiency. A general rule of thumb to ensure even distribution of loose media is to design the reactor such that the length-to-width ratio does not exceed 1.5:1 (WEF 2009).

Facilities must be provided to manage both loose and fixed MBBR media during annual basin maintenance. For the fixed media, a crane can be used to take media racks out of the basins to a storage location. The task of moving suspended media is more complex because there are more media pieces. The designer must provide space to store media when basins are being inspected and maintained.

For either fixed or loose media, media clogging can become problematic due to uneven mixing patterns. Once clogged, the biomass transitions from a thin to a thick biofilm with subsequent diffusion limitations. Proper scouring and mixing is required to maintain a thin biofilm. Thick biofilms decrease media surface area available for attachment and treatment. An example of fixed sheets with a thick biofilm is shown in Figure 5. This issue is more pronounced with fixed media systems as they are more difficult for scouring equipment to access areas between fixed media racks.

### Figure 5 - Example of a Thick Biofilm on Fixed Rope Media

In addition to media clogging, exit screens have a tendency to plug if not maintained clean. A means to overcome this plugging is by providing automatic air knife cleaning equipment at the screens.

Background on Fluidized Bed Biofilm Reactors

A fluidized bed biofilm reactor (FBBR) is a biological treatment process that uses carrier media to promote attached growth like the BAF and MBBR. FBBRs operate in an upflow mode with the media fluidized within the reactor. A schematic of a FBBR is shown in Figure 6. This configuration avoids plugging and provides scour to maintain a thin biofilm and improve mass transfer. Of the three groupings, a FBBR has the smallest footprint with detention times on the order of minutes. Despite such a small footprint, the FBBR suffers from scale-up issues and a lack of commercial systems (Sutton and Mishra 1994). A few scale-up issues are the required large height:width ratio (e.g., 1.35:1; WEF 2011b), pumping requirements to maintain the high recycle ratios (2-5 times influent flow; WEF 2011b), and even flow distribution (Kearney 2000).

Figure 6 – Fluidized Bed Biofilm Reactor Flow Schematic
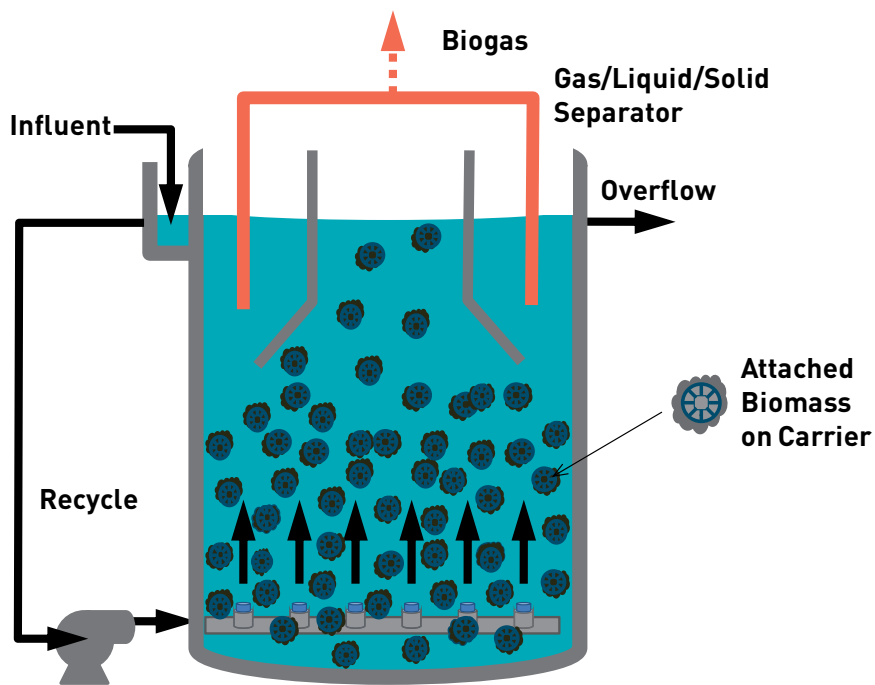
A FBBR is configured with vertical upflow that fluidizes the carrier media. Fluidization occurs as the drag force associated with the feed upflow exceeds gravity force down on the particle and lifts the carrier media. Lifting the media maximizes media exposure between attached biomass and the feed stream. As a result, the mass transfer is enhanced.

Media fluidization separates the FBBR from either the BAF or MBBR. By not having a packed bed like BAF configurations, head loss and clogging is avoided (Shieh and Keenan 1986). Similar to the MBBR, a FBBR does not filter solids and thus might require downstream solids separation. Although a loose media MBBR system also suspends the carrier media in solution, an MBBR is inherently different from a FBBR since the MBBR flow is horizontal rather than vertical.

The carrier media selection governs the process sizing. Historically, the two carrier media of choice have been either silica sand or granular activated carbon (GAC). Silica sand is the smoother surface of the two, with a more uniform size coefficient, but has a higher density than GAC. Coahelso et al. (1992) compared the two media and found GAC to be diffusion-controlled as it had a tendency to create thicker biofilms, whereas the silica sand FBBR created a thinner, more even biofilm that was kinetically controlled (WEF 2010a). Interest has grown in the use of glassy coke as it is a rough surface to promote biomass attachment with a lower specific gravity than GAC (McQuarrie et al. 2007). Regardless of media type, the denitrification results from pilot studies using different media have been comparable with effluent NOx-N concentration less than 2 mg N/L (Coahelso et al. 1992).

Typical FBBR design loading values and results from full-scale facilities are provided in Table 4. The MLSS concentrations in FBBRs fall between 20,000 to 40,000 mg/L (Bosander and Westlund 2000).

Table 4 - Typical FBBR Loading Rates for Tertiary Denitrification							
Empty Bed Vertical Velocity m/h (ft/sec)	Applied NOx-N Loading g N/m2/d (lb N/sf/d)	Flow m³/d (mgd)	NOx-N Removal Rate g N/m²/d (lb/sf/d)	Effluent TN-N mg N/L (NOx-N, mg N/L)	Effluent TP mg P/L	Downstream Clarification	Reference
39 [a] (0.04)	10.4 (2.1)	142,000 (37.5)	9.36 (1.92)	9.36 (1.92)	0.48	Filtration	Bosander and Westlund 2000
—	—	—	—	3.9 [-]	0.39	Filtration	Pagilla et al. 2006
36-60 (0.03-0.05)	—	—	—	—	—	—	EPA 1993
30-36 (0.03-0.03)	—	—	—	—	—	—	Metcalf and Eddy 2003

Notes:
a. Silica Sand
b. Methanol Used as External Carbon Source

Source: WEF 2011b

FBBR Specific Design Considerations

A FBBR is highly sensitive to flow variability such as storm events, or even over daily diurnal flows because it affects fluidization. The internal recirculation is critical and it must be flow-paced to simultaneously maintain fluidization and HRT. A rule of thumb is to provide an internal recirculation that is not required under peak hour flow conditions. Thus, the range of internal

recirculation is governed by the extent of flow peaking factors. Typically, the internal recirculation loop ranges from 2 to 5 (based on peaking factors) with the maximum internal recirculation used during dry weather diurnal low flows. A high internal recirculation rate directly translates to high energy demand to maintain the fluidization.

A key design element to avoid short-circuiting and improve overall process performance is the influent flow distributor. The flow distributor controls uniform flow delivery to the fluidized media cross-sectional area while not being clogged from influent solids. A secondary clarification process that produces low TSS (<10 mg/L) from the clarifiers is critical for successful FBBR performance. Additionally, the energy associated with the influent flow needs to be dissipated to reduce turbulence that can slough biomass and create uneven media distribution.

Flow distributor designs have evolved considerably over the years. Since the FBBR's inception in the 1970s, distributors have included gravel on top of the plate (Jeris et al. 1981), downward facing nozzles to dissipate kinetic energy (Sigmund 1982, Dempsey et al. 2006), and the more recent usage of fractals to control the scaling and distribution of fluids (Kearney 2000).

FBBR bed dynamic are affected by the virgin particle characteristics as well as biofilm growth on the virgin particles. Biofilm growth on media increases the particle size, reduces the bulk density, and increases drag on the biofilm-covered particles (bioparticles), which together allow for fluidization at lower upflow velocities compared to those required for the virgin media. As the bed expands, porosity increases and velocity around particles decrease. The bed rises until porosity is too high and velocity too low, resulting in particle settling. The bed will continue to expand until it reaches an upper limit, after which biofilm control measures must be implemented. The sloughing of biomass is governed by bioparticle collisions, not due to fluid shearing (Shieh and Keenan 1986). The spacing between neighboring bioparticles increases with bed expansion, thus reducing bioparticle collisions.

Biofilm control strategies in FBBRs have evolved since their inception in the 1970s. Jeris et al. (1981) pumped bioparticles that migrated from the top of the bed into a screen which subsequently vibrated to separate media from biofilm. Others initially considered a centrifugal pump working in tandem with a cyclone (Sutton et al. 1981). Since these early ideas, airlift systems (Frijters et al. 2000) or the recycling of bioparticles by way of stripping them from the carrier during the turbulent recirculation passage (McQuarrie et al. 2007) have been developed.

WHAT IS LIMITING EFFLUENT TN CONCENTRATION AND DENITRIFICATION IN TERTIARY DENITRIFICATION SYSTEMS?

The primary challenges associated with achieving both low TN and low TP with a tertiary denitrification process include:

- Recalcitrant Forms of Nitrogen
- Adequate Nutrients
- Partially Denitrified Versus Full Nitrogen Load as Nitrate
- Final Barrier of Treatment Prior to Disinfection
- Ammonia Bleed Through from Upstream Process (Partial Nitrification)

Recalcitrant Forms of Nitrogen

Recalcitrant organic nitrogen is the portion resistant to biological or chemical transformation in the wastewater treatment process and results in a significant fraction of effluent soluble organic nitrogen (SON) for systems aiming for low effluent TN concentrations. Reported effluent rSON concentrations have ranged from 0.5 to 2.8 mg N/L (WERF 2019c), so that in some cases effluent SON can present a particular challenge to meeting low effluent TN limits. Effluent SON composition, concentrations, treatability, and bioavailability have been a focus of the Nutrient Challenge. Refer to the WERF compendium on SON in biological nutrient removal wastewater treatment processes (Nutrient Removal Challenge 2019c) for more detail.

Adequate Nutrients

Sufficient macronutrients—carbon, nitrogen, and phosphorus—are required to sustain biological growth and nitrogen removal in tertiary denitrification processes. This section focuses on phosphorus requirements in tertiary denitrification processes for facilities with low TN and TP limits. Carbon sources are addressed in the subsequent section. Nitrogen is present in excess in tertiary denitrification influents and thus nitrogen limitation is not problematic if external carbon dosing is appropriately controlled.

For many BNR applications, both low effluent TP and TN concentrations are required. If the final chemical treatment step occurs before or concurrent with the tertiary denitrification process and is aimed at achieving a very low effluent TP concentration, it is possible that insufficient phosphorus remains to support the biological growth needed in the final fixed film denitrification process to reduce the required amount of NOx-N. One approach to avoid a phosphorus limitation is to place the final chemical phosphorus removal step after tertiary denitrification. An example of such an approach is a denitrifying MBBR followed metal salt addition and media filtration. In other circumstances, the final chemical or enhanced biological phosphorus removal step may occur prior to the tertiary denitrification process, and the risk of phosphorus limitation is

heightened. In addition to reactive phosphorus (PO₄-P) for growth needs, bioavailable phosphorus in tertiary denitrification processes may come from particulate phosphorus hydrolysis, endogenous decay, and dissolution or dissociation of chemically sorbed phosphorus as later discussed.

The ratio phosphorus required per mass of NOx-N removed (g P/g NOx-N) is often used to evaluate potential phosphorus limitation. A drawback of such a ratio is that the ratio is affected primarily by yield on the external carbon source but also environmental conditions such as temperature, which affects decay and thus net yield. The following approach can be used estimate of the P/NOx-N ratio that may limit denitrification. As an example for methanol addition: assuming 4.5 g methanol COD per g of NOx-N removed, 0.29 g VSS produced per g of methanol COD oxidized, and 0.022 g P per g of VSS produced (Copp & Dold 1998), the estimated P/NOx-N requirement is 0.029 g P/g NOx-N reduced. This simple calculation provides some guidance but does not capture complex reactions in tertiary denitrification biofilms. Key findings from several studies are presented below to highlight the range of P/NOx-N ratios observed in practice without and with tertiary chemical phosphorus removal.

Studies in tertiary denitrification processes without chemical addition for phosphorus removal have shown limiting PO₄-P/NOx-N ratios in the range of 0.01 to 0.02 g P/g N. During pilot testing of continuous backwash denitrification filters at the Hagerstown, MD, WWTP, the effluent NOx-N concentration remaining in the effluent stream increased when the influent PO₄-P/NOx-N ratio dropped below 0.02 g P/g N (deBarbadillo et al. 2006). The authors noted that the secondary effluent feed to the filters contained solids from the upstream biological phosphorus removal process and that some phosphorus could potentially be released in the filter bed. The authors also reviewed operating data from the H.L. Mooney WRF (Virginia) and Truckee Meadows WRF (Nevada). These data also supported an apparent PO₄-P/NOx-N threshold of between 0.01 to 0.02 g P/g N, below which deterioration in denitrification performance was observed. Husband and Becker (2007) evaluated deep-bed denitrification filters in Arlington, Virginia. The filter was able to significantly reduce influent nitrate loads under average conditions without supplemental phosphorus and required from 0.01 to 0.02 mg PO₄-P/mg NOx-N. The authors noted that the filter responded slowly to rapid increase in nitrate loads and showed higher PO₄-P uptake during the step increase in nitrate loading (approximately 0.03 mg PO₄-P/mg NOx-N). Boltz et al. (2009) evaluated various datasets from tertiary denitrification processes and concluded the minimum threshold for P limitation was 0.009 g P/g NOx-N.

Studies in tertiary denitrification processes with upstream or concurrent chemical addition for phosphorus removal have shown lower limiting PO₄-P/NOx-N ratios less than 0.01g P/g N. Scherrenberg et al. (2008) reported that denitrification in a continuous backwash denitrification filter with upstream ferric chloride addition could be maintained at an apparent PO₄-P/NOx-N ratio as low as 0.005 g P/g N when accounting for secondary effluent phosphorus removed by

ferric dosing. In subsequent work, Scherrenberg et al. (2009) studied phosphorus limitation in two downflow static bed denitrification filter configurations with poly-aluminum chloride dosing for phosphorus removal. Profile sampling for NO_3-N, NO_2-N and PO_4-P through the depth of the media suggested phosphorus limitation occurred at PO_4-P/NO_x-N ratios of 0.006 g P/g N, where NO_2-N accumulation occurred. In bench-scale studies using mixed liquor from the Washington, DC, Blue Plains second stage nitrification/denitrification activated sludge process, Murthy et al. (2005) showed that both nitrification and denitrification rates were comparable between control reactors (with excess PO_4-P) and reactors in which co-precipitation of phosphorus using ferric chloride was used to reduce PO_4-P concentrations to 0.03 mg P/L or lower. Murthy et al. (2005) concluded that the kinetics of dissolution/dissociation of the chemically sorbed phosphorus is likely more rapid than the rate of uptake by slow-growing methanol-degrading bacteria. Thus, chemically sorbed phosphorus entering tertiary denitrification processes may become available for biological growth requirements.

PO_4-P concentrations less than 0.1 mg P/L may limit fixed film tertiary denitrification processes. Simultaneous phosphorus precipitation and denitrification was evaluated in upflow filters near Stockholm (Hultman et al. 1994, Jonsson et al. 1997, Jonsson 1998). It was estimated that 0.1 mg PO_4-P/L was sufficient for biological activity under the conditions tested, while denitrification performance was adversely impacted at 0.03 mg PO_4-P/L. Nordeidet et al. (1994) observed a similar threshold in nitrifying rotating biological contactors, where nitrification was impacted at PO_4-P concentrations below 0.15 mg P/L.

The studies above show that phosphorus transformations in tertiary denitrification processes are complex and that tertiary denitrification can be sustained at low PO_4-P concentrations and at lower apparent P/NO_x-N ratios than otherwise predicted by simple estimates. Additional work is needed to fully understand the impacts and mechanisms whereby denitrification is sustained when the available phosphorus is less than the stoichiometric requirement. While experience shows that denitrification can be sustained under such conditions, provisions to add supplemental phosphorus are a prudent measure and may be required in these cases. For example, the Truckee Meadows WRF (Reno, Nevada) has periodically dosed phosphoric acid to their fluidized bed denitrification reactors to counteract reduced denitrification removal performance associated with phosphorus limitation.

●●●● CARBON SOURCES FOR TERTIARY DENITRIFICATION

The supplemental carbon source is vital to system operation, for tertiary denitrification process. Examples of external carbon feed sources are as follows (Gu et al. 2010):

• Pure Chemicals (e.g., Methanol, Ethanol, Acetate, Sugar, and Butanol)
• Commercially Available (e.g., Unicarb, Micro C™, etc.)
• Raw Industrial/Agricultural Byproducts (e.g., Corn Syrup, Molasses, Brewery Waste, etc.)
• Sludge Fermentation Products
• Electron Donors (e.g., Hydrogen Gas, Methane, etc.)

The Nutrient Challenge addressed protocols to evaluate external carbon sources for denitrification (Gu et al. 2010). The selection of carbon source is governed by a combination of cost, safety, dose control, and tertiary denitrification process type. Delivering the proper external carbon feed dose is important to avoid sCOD breakthrough leaving the tertiary process and potentially increasing effluent BOD. The denitrification COD requirement depends on various factors including the carbon substrate type and its associated bacterial yield. The COD requirement for denitrification varies depending on the carbon substrate used and the associated yield. The reader is referred to other Nutrient Challenge documents addressing external carbon sources, observed yields, and methods to determine yield coefficients for alternative carbon sources (Gu et al. 2010 Nutrient Removal Challenge 2019d).

Carbon Addition Control to Tertiary Denitrification Processes
Different approaches to control the external carbon dose to the denitrification process can be used. The ability to meet low TN limits and avoid external carbon overdose and bleed-through is affected by the control approach selected. The approaches vary in complexity, extent of instrumentation, and control philosophy used and include the following: 1) manual control, 2) flow-paced control, 3) feed-forward control using flow and influent nitrate concentration, and 4) feed-forward and feedback control using flow, influent nitrate concentration, and effluent nitrate concentration. These external carbon addition control approaches are described below with their corresponding strengths and weaknesses.

Manual Control
For manual control of chemical dosing, all pumping rate adjustments and sampling are performed manually. Based on a certain level of nitrate removal, the operator manually calculates the external carbon dose (lb/d) required and the corresponding pumping rate and manually sets the external carbon feed pump. For tertiary denitrification processes, there is risk of increase in the effluent BOD bleed-through if external carbon is overdosed and if tertiary influent nitrate and nitrite concentrations are low. This strategy is not recommended for stringent NOx-N discharge limits.

Flow-Paced Control

Flow-paced control represents the most basic type of automated control. The operator manually calculates the average external carbon dose (lb/d) required and the corresponding average external carbon pumping rate. The control system is set to modulate the pumping rate up and down with diurnal fluctuations in wastewater flow. Generally this should only apply to dry weather operation, and external carbon dosages should not be increased above that required to meet the daily maximum hour of the dry weather diurnal curve. This level of automatic control is relatively simple, and may be adequate for moderate discharge limits. However, a higher level of control is recommended for plants with stringent effluent BOD or NOx-N limits.

Feed-Forward Control

A feed-forward control scheme offers the next level of automatic control. The denitrification influent nitrate concentration is measured and used in combination with flow rate measurement to continuously vary the external carbon feed rate. Because the external carbon dose is based on both wastewater flow and NOx-N concentration, it is feasible to operate in this mode during dry and wet weather flows. Although the Manual for Nitrogen Control (EPA 1993) suggested that reliance on online instruments for measuring nitrate could be a weak link in this control approach, advancements in online instrumentation for monitoring NOx-N concentrations have made this a more reliable means of control.

Feed-Forward and Feedback with Effluent Concentration Control

This represents the most complex level of chemical feed control. The system is designed to operate continuously in the flow-paced or feed-forward (flow and influent concentration) modes, with a correction at discrete intervals to achieve an effluent concentration setpoint. This operating strategy offers tight control of external carbon dosage to allow WWTPs to meet low nitrate levels without increasing the effluent BOD or total organic carbon. As with the feed-forward control, reliability of online nitrate monitoring was initially the weak link; however, since initial implementation with older-generation instruments, this mode of control has been successfully applied at a number of tertiary denitrification installations.

OPERATIONAL ISSUES FOR TERTIARY DENITRIFICATION PROCESSES

Although the three groups of tertiary denitrification technologies operate differently, there are several key operational issues and considerations, many common amongst the technologies, which impact their performance (WEF 2011b) as listed and described below:

• Avoid $N_{2(g)}$ Build-Up (BAF; Only Downflow)
• Maintain Enough Denitrifiers by Avoiding Excess Backwashing or Scouring (BAF, MBBR, and FBBR)
• Avoid Solids Breakthrough (BAF, MBBR, and FBBR)
• Limit NO_3^-/NO_2^- Breakthrough (BAF, MBBR, and FBBR)
• External Organic Carbon Breakthrough (BAF, MBBR, and FBBR)
• Peak Flow Management (BAF, MBBR, and FBBR)

Dissolved $N_{2(g)}$ build-up increases head loss in downflow BAFs and thus should be avoided. Dissolved $N_{2(g)}$ build-up does not occur in upflow BAFs, MBBRs, or FBBRs since the upwards or horizontal flow and/or agitation by mechanical mixing releases biologically-mediated gas bubbles to the atmosphere during normal operation. A means to overcome this dissolved $N_{2(g)}$ build-up is by more frequent backwash cycles and/or by performing nitrogen removal in the upstream activated sludge process to reduce NOx-N loading on the tertiary denitrification filter.

Backwashing frequency for BAF and scouring for MBBR are related in terms of operations impact. It is a balancing act between minimizing costs associated with backwash/scour and maintaining the appropriate amount of denitrifier biomass. Facilities that backwashing/scour too frequently have higher operational costs. Additionally, frequent backwash/scour events can lead to inadequate biomass levels in the systems, especially immediately following a backwash/scour event. During those events, excess biomass is removed and the microbial community is 'shocked' resulting in less biomass per nitrate. On the other end of the spectrum, insufficient backwash/scour may result in solids buildup and thick biofilms that are diffusion-limited with poor removal performance and are more prone to large sloughing events.

Solids breakthrough in any of the three tertiary denitrification processes is an indicator of excess solids in the units. For BAFs designed for filtration capacity, solids breakthrough indicates that backwash frequency should be increased. In the case of moving beds (e.g., FBBR or MBBR), solids breakthrough is associated with large sloughing events in contrast to routine solids production at a relatively consistent rate and indicates that bed turnover rates should be increased to better control biofilm thickness to avoid such sloughing events.

NOx-N breakthrough may be attributed to one or more of the following conditions: inadequate biomass or hydraulic retention time, insufficient external organic carbon dosing, elevated influent DO concentrations, and/or nutrient limitations. Denitrification rates will decrease as the extent of these conditions increases.

External organic carbon breakthrough may be attributed to one or more of the following conditions: inadequate biomass or hydraulic retention time, nutrient limitations, and/or improper external carbon dosing. An inadequate amount of biomass or nutrients such as nitrogen, phosphorus, or trace elements will slow or stop denitrification and lead to external carbon breakthrough. Additionally, external carbon dosing above that required for denitrification will not be consumed in the denitrification process and appear as effluent BOD if not otherwise removed in an aerobic biological polishing step.

During peak flow events, the hydraulic detention time is reduced and the head loss increased. For all three tertiary denitrification technologies, denitrification capacity is reduced at peak flows as a consequence of shorter detention time. The proper design of such systems should account for peak flow events.

●●●● WHAT ARE THE KEY DESIGN CRITERIA?

Most tertiary denitrification system designs are based on rules of thumb or the designer's experience from operating systems. The rules of thumb derived from literature and equipment manufacturers for BAF, MBBR, and FBBR were provided above in Table 1, Table 3, and Table 4, respectively.

A pilot is highly recommended prior to designing a system to meet low TN/TP levels. Once piloted and implemented, the operations and controls must be optimized. The reader is referred to Tsuchihashi et al. (2015) for experiences with online carbon addition strategies and control.

●●●● WHAT PERFORMANCE CAN RELIABLY BE ACHIEVED?

Bott and Parker (2011) evaluated the performance of tertiary denitrification processes as part of the Nutrient Challenge. Table 5 shows the range for 50th and 95th total nitrogen performance statistics using 3 years' data from full-scale plants. The average (50th percentile) performance as low as 1.15 mg/L at one facility. At the reliable performance (95th percentile) these facilities achieved 2.7 to 4.2 mg/L.

Table 5 - Denitrification Technology Performance Statistics for Full-scale Plants			
Plant/Source	**Process**	**50th Percentile TN (mg/L)**	**95th Percentile TN (mg/L)**
Fiesta Village, FL	Denitrification Filter	1.0	2.7
Truckee Meadows WRF, NV	Fluidized Bed	1.6	2.9
Scituate, MA	Denitrification Filter	2.4	4.2
Martis Valley T-TSA, CA	Tertiary BAF	2.5	3.4
Jimenez et al. 2007	5 A2/O Plants with Denitrification Filters in FL	—	3.0

Source: adapted fromBott and Parker 2011

●●●● FUTURE RESEARCH

Tertiary denitrification processes can effectively reduce effluent nitrate and nitrite. Studies of full-scale tertiary denitrification systems suggest that low effluent TN and TP concentrations can be achieved, but that the nature of upstream or simultaneous phosphorus removal processes impact the apparent phosphorus nutrient requirement for denitrification. Tertiary denitrification processes are often designed based on empirical approaches but nonetheless can achieve low effluent TN concentrations. The following research needs have been identified:

- Confirm the PO_4-P/NO_x-N ratio required to meet growth requirements based on field data, data from controlled laboratory studies, and theory.
- Improve understanding of the role of biologically stored P and chemically sorbed P in the denitrification process. To what extent is phosphorus released during the tertiary denitrification process? To what extent is chemical P available for biological growth? How can these phenomena be better predicted to inform tertiary denitrification process design and "apparent" nutrient requirement?
- Better characterization of P speciation to advance removal strategies to meet ultra-low level TP discharges (<0.010 mg P/L TP) and identify fraction of TP available for biological growth in tertiary denitrification processes. Refer to other Nutrient Challenge compendia for background and related research needs (WRF 2019a, 2019b)
- Best practices for integrating biofilm models in design of tertiary denitrification systems.
- Assessment of the role of effective media surface area on denitrification. Media is typically evaluated based on the 'naked' surface area, but fails to consider surface chemistry, roughness, hydraulic distribution, and other factors that affecting biofilm growth on the media.
- More rigorous statistical performance evaluation of impact of carbon dose control strategy and setpoints on NO_x-N removal. Is current dataset biased by control strategy or TN limit effectively allowing for some NO_x-N in the final effluent? What are the lowest NO_x-N concentrations that can be achieved with versus without routine bleed-through of external carbon?
- Use of inorganic electron donors (e.g., hydrogen gas) as alternative to external organic carbon electron donors for tertiary denitrification.

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