Trickling Filters: Achieving Nitrification

Project funded by the U.S. Environmental Protection Agency under Assistance Agreement No. CX824652

Fact Sheet

Introduction

Commencing with the Federal Water Pollution Act of 1965, a series of environmental legislative reforms resulted in a consistent national approach to pollution control based on water quality and beneficial use goals. These goals resulted in national, technology-based standards, requiring a minimum level of secondary treatment for such conventional wastewater parameters as biochemical oxygen demand (BOD) and suspended solids (SS).

Requirements for advanced treatment, such as ammonia removal (nitrification) or total nitrogen removal, are based on specific water quality needs for a given receiving water. Technology-based standards do not exist for nitrogen, as they do for SS and BOD, because of the varied nature of nitrogen's effect on receiving waters.

One of the oldest wastewater treatment processes used in the U.S. and around the world (first used in England in 1893) is the trickling filter (TF). The TF is an aerobic treatment system utilizing microorganisms attached to a media to remove organic matter from wastewater that passes over, around, through, or by the media. This type of system is typical of a number of technologies (e.g., rotating biological contactors and packed bed reactors).

These systems are known as attached-growth processes, in contrast to systems where microorganisms are sustained in a liquid, and are thus known as suspended-growth processes. Since the TF is the most common attached-growth process, it will be discussed here, although the same principles would apply to the other attached-growth systems.

When excess nutrients became a concern, it became necessary to adapt "conventional" sewage treatment systems to meet the increased oxygen demand placed on receiving waters by high ammonia nitrogen concentrations in wastewater effluents. TFs and other attached-growth processes proved to be well-suited for the removal of ammonia nitrogen by oxidizing it to nitrate nitrogen (nitrification).

Nitrogen Content in Wastewater

Nitrogen exists in many forms in the environment and can enter aquatic systems from either natural or human-generated sources. Some of the primary direct sources or transport mechanisms of nitrogen from sewage are listed below:

- Untreated sewage—direct discharge
- Publically owned treatment works (POTW) effluent—direct discharge, land application
- POTW waste solids—direct discharge, land application
- Septic tanks and leaching fields—groundwater movement

Untreated sewage flowing into a municipal wastewater facility normally consists of 20 to 85 mg/L of total nitrogen. The nitrogen in domestic sewage is approximately 60% ammonia nitrogen, 40% organic nitrogen, and small quantities of nitrates.

Treated domestic sewage will have varying levels of nitrogen, depending on the method of treatment used. Most treatment plants decrease the level of total nitrogen via cell synthesis and solids removal. However, unless there is a specific treatment provision for nitrification, most of the ammonia nitrogen passes through.

For treatment plants that do nitrify, an additional tertiary process called denitrification (the conversion of nitrate nitrogen to nitrogen gas) can lower the total nitrogen content to 10 to 30% of influent levels. Effluent that has received secondary treatment typically contains 15 to 35 mg/L of total nitrogen. Advanced biological nitrification-denitrification techniques can usually achieve 2 to 10 mg/L of total nitrogen in the effluent.

Some effects of nitrogen in discharges from wastewater facilities include ammonia toxicity to aquatic life, adverse public health effects, and decreased suitability for reuse.

Biological Nitrification

Nitrification is a process in which ammonia nitrogen in wastewater is oxidized first to nitrite nitrogen and then to nitrate

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nitrogen by autotrophic bacteria. Nitrification starts when the soluble BOD concentration in the wastewater is low enough for nitrifiers to compete with heterotrophs, which derive energy from the oxidation of organic matter. Listed below are the two steps involved in the nitrification process and the equations for these reactions:

1) Ammonia is oxidized to nitrite (NO_2^-) by *Nitrosomonas* bacteria.

$$2\ NH_4^+ + 3\ O_2^- \longrightarrow 2\ NO_2^- + 4\ H^+ + 2\ H_2O$$

2) The nitrite is converted to nitrate (NO_3^-) by *Nitrobacter* bacteria.

$$2\ NO_2^- + O_2 \longrightarrow 2\ NO_3^-$$

These two reactions supply the energy that the nitrifying bacteria need for growth.

Trickling Filters: Process Description

A TF consists of a permeable media made of a bed of rock, slag, or more recently, plastic over which wastewater is distributed and trickles through (see Figure 1). Rock or slag beds can be up to 200 feet in diameter and 3 to 8 feet deep with rock size varying from 1 to 4 inches. Packed plastic filters are narrower and deeper (14 to 40 feet), more like towers, with the media in various configurations (e.g., vertical flow, cross flow, or various random packings). Although rotary distribution is essentially standard for the process, fixed distributors are also used in square or rectangular reactors.

A TF design also includes an open underdrain system that collects the filtrate as well as solids and also serves as a source of air for the microorganisms on the filter. The treated wastewater and solids are piped to a settling tank where the solids are separated. Usually part of the liquid from the settling chamber is recirculated to the TF to dilute the incoming wastewater, keep the filter moist, or in many cases, for process optimization. It is essential that sufficient air be available for the successful operation of the TF. It has been found that natural draft and wind forces are usually sufficient if large enough ventilation ports are provided at the bottom of the filter and the media has enough void area.

The organic material in the wastewater is adsorbed by a population of microorganisms (aerobic, anaerobic, and facultative bacteria; fungi; algae; and protozoa) attached to the media as a biological film or slime layer (approximately 0.1 to 0.2 mm thick). This film is formed, as the wastewater flows over the media, from microorganisms already in the liquid that gradually attach themselves to the rock, slag, or plastic surface. Organic material is degraded by the aerobic microorganisms in the outer part of the slime layer.

As the layer thickens (with microbial growth), oxygen cannot penetrate to the media face, and anaerobic organisms develop. As the biological film continues to grow, the microorganisms next to the surface lose their ability to cling to the media, and a portion of the slime layer falls off the filter. This is known as sloughing and is the main source of solids picked up by the underdrain system.

The two general types of TF nitrification configurations are single-stage and two- (or separate-) stage.

- *Single-stage:* Carbon oxidation and nitrification take place in a single TF unit.

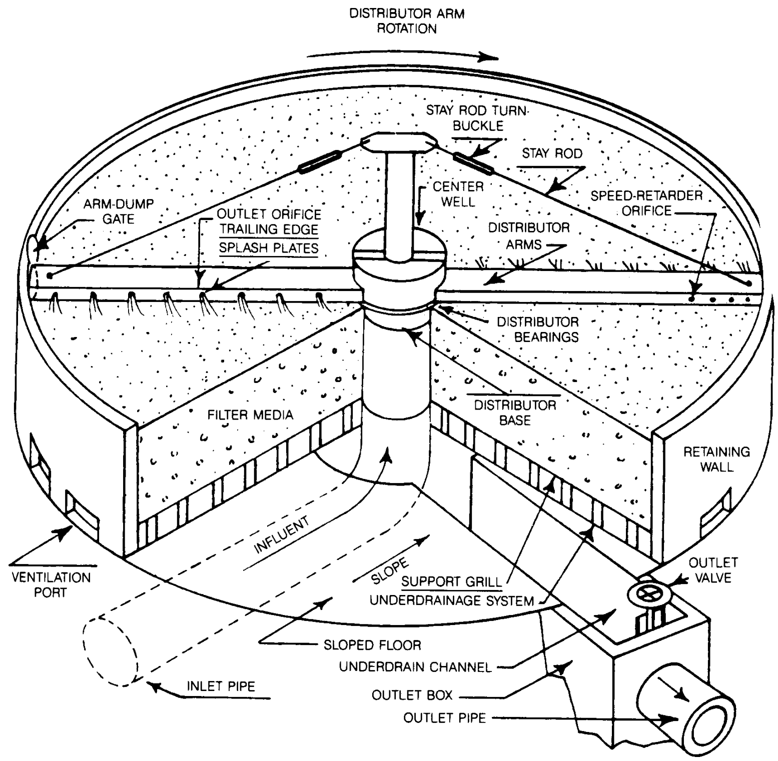

Figure 1: Schematic of a Trickling Filter

Source: Water Environment Federation (1996), copyright © WEF, reprinted with permission

- *Two- (separate-) stage:* Reduction of carbonaceous BOD (CBOD) occurs in the first treatment stage, and nitrification occurs in the second stage.

Numerous types and combinations of treatment units are found in practice depending on permit requirements, site conditions, historical development, designer experience, etc. In general, however, a single-stage TF has to remove organic carbon or CBOD in the upper portion of the unit and provide nitrifying bacteria for nitrification in the lower part.

Since the influent is necessarily of high organic strength (i.e., receiving primary treatment only), it has to be applied at a rate low enough to achieve both CBOD removal and nitrification sufficient for required effluent quality. A two-stage system allows for greater process flexibility, since each stage can be operated independently, and the flow regime can be varied to achieve the best results.

Advantages and Disadvantages

Some advantages and disadvantages of TFs are listed below:

Advantages

- Simple, reliable process that is suitable in areas where large tracts of land are not available for a treatment system
- May qualify for equivalent secondary discharge standards
- Effective in treating high concentrations of organics depending on the type of media used
- Appropriate for small- to medium-sized communities and onsite systems
- High degree of performance reliability
- Ability to handle and recover from shock loads

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- Durability of process elements
- Relatively low power requirements
- Level of skill and technical expertise needed to manage and operate the system is moderate

Disadvantages

- Additional treatment may be needed to meet more stringent discharge standards
- Generates sludge that must be treated and disposed of
- Regular operator attention needed
- Relatively high incidence of clogging
- Relatively low loadings required depending on the media
- Limited flexibility and control in comparison with activated-sludge processes
- Potential for vector and odor problems

Performance and Application

The performance of the nitrification process is dependent on a number of factors. These include the availability of oxygen (i.e., adequate ventilation), level of CBOD, ammonia nitrogen concentration, media type and configuration, hydraulics of the TF, temperature, and pH.

Single-Stage Nitrification

To achieve adequate nitrification in a single-stage TF, the organic volumetric loading rate must be limited to the approximate ranges shown in Table 1. Filters with a plastic media have greater surface contact area (approximately 80%) per unit volume than do rock or slag, and therefore, can achieve the same degree of nitrification with higher organic loadings. Plastic media can also provide for better ventilation and thus, improved oxygen transfer.

Table 1: Typical Loading Rates for Single-Stage Nitrification

TF Media	% Nitrification	Loading Rate lb BOD/1,000 ft^3/d (g BOD/m^3/d)
Rock	75–85	10–6 (160–96)
	85–95	6–3 (96–48)
Plastic	75–85	18–12 (288–192)
Tower TF	85–95	12–6 (192–96)

Adapted from: Metcalf & Eddy, Inc. (1991) with permission from The McGraw-Hill Companies

Stockton, California

TFs are usually designed with minimum effluent recycling capabilities to maintain stable hydraulic loading during normal seasonal operations. In Stockton, California, an increase in nitrification was noted when the recirculation ratio was increased as well as the air circulation. These two changes also increased the dissolved oxygen (DO) concentration, which enhanced overall treatment performance.

The importance of the DO concentration in the operation of all TFs highlights the need for sufficient ventilation. At high carbonaceous feed concentrations, the effects of pH and temperature are often masked by the DO concentration. By ensuring that the effluent alkalinity is equal to or greater than 50 mg/L, as calcium carbonate ($CaCO_3$), significant pH effects can be avoided. The effect of temperature is usually neglected when it is above 15˚ C.

Amherst Wastewater Treatment Plant

The Amherst Wastewater Treatment Plant (AWTP) located in Amherst, Ohio, had two TFs operating in series with no intermediate clarification. As such, they were considered a single-stage TF system. The filters were each 40 feet wide, 90 feet long, and 17 feet deep, with plastic cross-flow media.

At the time of the study, the plant was operating at a design flow of 2 million gallons per day (mgd) with a hydraulic loading rate averaging 23.0 m^3/m^2/d (565 gpd/ft^2). The plant was required to meet an effluent ammonia nitrogen limit of 6 mg/L in the winter and 3 mg/L during the summer. Temperatures for October through May ranged between 8˚ and 15˚ C, while the summer month temperatures ranged between 17˚ and 20˚ C.

Average monthly effluent ammonia nitrogen values during colder temperature periods varied from 1.8 to 4.9 mg/L. The AWTP results indicated a temperature dependency for nitrification below 15˚ C. However, the treatment plant consistently met ammonia removal requirements at loadings generally associated with nitrification design practices.

Results from full-scale studies indicate an improvement in performance when recirculation was practiced using rock or slag media. Specific surface area also has an effect on nitrification—higher specific areas for plastic media enable nitrification at higher volumetric loadings. Another factor favoring plastic media filters is their enhanced oxygen transfer.

Two-Stage Nitrification—Allentown, Pennsylvania

A treatment facility in Allentown, Pennsylvania, was required to meet effluent ammonia nitrogen limits of 3 mg/L in the warmer months and 9 mg/L during colder months. This facility was designed for an average flow of 40 mgd with an effluent BOD_5 limit of 30 mg/L.

The various unit processes in this facility included screening, grit removal, primary clarification, first-stage TF, intermediate clarification, second-stage TF, final clarification, and chlorine disinfection.

The first stage had four plastic media TFs in parallel, while the second stage had a single large rock filter. A recycle ratio of 0.2:1 was practiced only on the second-stage TF. Temperatures during the warmer months ranged between 17˚ C and 19˚ C and during the colder months temperatures varied from 11˚ and 16˚ C.

The BOD_5 loading in the first stage during the study period was high, averaging 66 lb/1,000 ft^3/d, with an equivalent NH_4-N loading of 6.7 lb/1,000 ft^3/d. The average first-stage effluent BOD_5 concentrations during warmer and colder periods were 50 and 73 mg/L, respectively, with associated NH_4-N levels of 10.0 and 11.4 mg/L, respectively.

The BOD_5 loading in the second stage averaged 8.5 lb/1,000 ft^3/d. The average monthly effluent BOD_5 concentration was consistent throughout the study year, ranging between 6 and 18 mg/L. The effluent NH_4-N level averaged 4.7 mg/L during the warmer months and 5.9 mg/L during the colder months. This plant was able to consistently meet its effluent BOD_5 standard throughout the study.

Nitrification process reliability is directly related to CBOD loading. Low levels of organics in the influent to two-stage, attached-growth reactors can potentially eliminate the need for intermediate solid-liquid separation between the

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stages. Short-circuiting is less of a concern because clogging of voids in the media is also reduced.

In the absence of significant carbonaceous BOD_5 loadings (e.g., in the second stage of a two-stage system), the rate of nitrification in attached-growth reactors is influenced by the concentration of both ammonia nitrogen and DO concentrations in the liquid phase. The reported effect of temperature is varied for TFs operating at low CBOD levels by factors such as oxygen availability, influent and effluent ammonia nitrogen concentration, and hydraulic loading conditions.

The minimum hydraulic loading needed to ensure complete wetting of the TF surface is related to the characteristics of the media. Cross-flow media are favored over vertical-flow media due to their greater oxygen transfer efficiency and higher specific surface area.

Operation and Maintenance

Although TFs are generally reliable processes, there is still a potential for operational problems. Common operating problems can be caused by increased growth of biofilm, changes in wastewater characteristics, improper design, or equipment failures. Listed below are some common problems followed by possible causes and corrective actions:

Disagreeable Odors from Filter

- *Excessive organic load causing anaerobic decomposition in filter*—Reduce loading; increase BOD removal in primary settling tanks; enhance aerobic conditions in treatment units by adding chemical oxidants, preaerating, recycling plant effluent, or increasing air to aerated grit chambers; scrub off-gases; use plastic media instead of rock
- *Inadequate ventilation*—Increase hydraulic loading to wash out excess biological growth; remove debris from filter effluent channels, underdrains, and the top of filter media; unclog vent pipes; reduce hydraulic loading if underdrains are flooded; install fans to induce draft through filter; check for filter plugging resulting from breakdown of media

Ponding on Filter Media

- *Excessive biological growth*—Reduce organic loading; increase hydraulic loading to increase sloughing; use high-pressure stream of water to flush filter surface; maintain 1 to 2 mg/L residual chlorine on the filter for several hours; flood filter for 24 hours; shut down filter to dry out media; replace media if necessary; remove debris

Filter Flies (Psychoda)

- *Inadequate moisture on filter media*—Increase hydraulic loading; unplug spray orifices or nozzles; use orifice opening at end of rotating distributor arms to spray filter walls; flood filter for several hours each week during fly season; maintain 1 to 2 mg/L residual chlorine on the filter for several hours
- *Poor housekeeping*—Mow area surrounding filter and remove weeds and shrubs

Icing

- *Low temperature of wastewater*—Decrease recirculation; use high-pressure stream of water to remove ice from orifices, nozzles, and distributor arms; reduce number of filters in service as long as effluent limits can still be met; reduce retention time in pretreatment and primary treatment units; construct windbreak or covers

Rotating Distributor Slows Down or Stops

- *Insufficient flow to turn distributor*—Increase hydraulic loading; close reversing jets
- *Clogged arms or orifices*—Flush out arms by opening end plates; remove solids from influent wastewater; flush out orifices
- *Clogged distributor arm vent pipe*—Remove material from vent pipe by rodding or flushing; remove solids from influent wastewater
- *Distributor arms not level*—Adjust guy wires at tie rods
- Distributor rods hitting media—Level media; remove some media

Rotary distributors are very reliable and easy to maintain. A clearance of 6 to 9 inches is needed between the bottom of the distributor arm and the top of the media bed to allow the wastewater from the nozzles to spread out and cover the bed uniformly. This also prevents ice from accumulating during freezing weather.

Care should be taken to prevent leaks. Follow the manufacturer's operation and maintenance (O&M) instructions on pumps, bearings, and motors. All equipment must be tested and calibrated as recommended by the equipment manufacturer. A routine O&M schedule should be developed and followed for any TF system. It is critical that a TF system be pilot tested prior to installation to ensure that it will meet effluent discharge permit requirements for that particular site.

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For more information on trickling filters or a list of other fact sheets, contact the NSFC at West Virginia University, P.O. Box 6064, Morgantown, WV 26506-6064. Phone: (800) 624-8301 or (304) 293-4191. Fax: (304) 293-3161. World Wide Web site: http://www.nsfc.wvu.edu.

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