# Nitrogen Wastewater Treatment by Decentralized Coastal Florida Communities

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**After reading this you will be able to:**

- **Explain why nitrogen removal from wastewater is important for the protection of both public health and the environment**
- **Explain different methods/technologies of nitrogen reduction/removal**
- **Explain what passive nitrogen removal technologies are, why they are preferred, and list examples**
- **Be able to choose the best technology for a specific area**

Nitrogen can severely influence water quality and is a concern for both public health and the environment. Nitrate-nitrogen, also referred to as reactive nitrogen, is the most common form of nitrogen contamination in both surface and groundwater, although ammonia and nitrite can also be sources of nitrogen contamination. Nitrogen contamination can have adverse human health effects if consumed in large quantities over a short period of time (e.g. cyanosis of infants, "blue baby syndrome") or in lower quantities over a longer duration (e.g. cancer). Environmental problems caused by nitrogen contamination include toxic effects to aquatic organisms (ammonia-N), low dissolved oxygen, and eutrophication—all of which can cause massive fish kills and alter the natural ecosystem (United Sates Environmental Protection Agency [US EPA], 2008; Univeristy of California at Davis [UC Davis], 2010).

## Introduction

Onsite sewage treatment and disposal systems (OSTDS), commonly referred to as septic systems, have been identified as one source of nitrogen loading to aquatic environments. This may be of a particular concern in Florida due to its karst topography and geology, and increasing populations among coastal communities. Urban sprawl pushes communities farther from central wastewater treatment centers and it becomes more cost effective to use an OSTDS— approximately 30% of all new developments in the US utilize an OSTDS (Hazen and Sawyer, 2009a). OSTDS are one of the largest groundwater recharges for the state, which is important seeing as approximately 90% of drinking water in Florida is from groundwater. (Florida Department of Health [FDOH], 2010)

The Florida Department of Health (FDOH) is in charge of protecting public health and the environment. Protection of groundwater from further nitrogen contamination due to OSTDS is a priority for FDOH to achieve its above mission. For this reason, FDOH has recently been conducting a study, "Florida Onsite Sewage Nitrogen Reduction Strategies (FOSNRS) Study" to research cost-effect nitrogen reduction solutions. Passive nitrogen removal strategies are preferred over active methods for several reasons. First, they require less maintenance and operation by the user, which increases the likelihood and effectiveness of their prolonged use over time. Second, active technologies can further impact nitrogen contamination due to their energy requirement and associated nitrogen production and atmospheric deposition to water source—atmospheric deposition has been estimated to contribute about 30% of total nitrogen loading to open waters for the Tampa Bay area (Janicki et al., 2001). For the purposes of the FOSNRS study and future applications, FDOH has defined "passive" technologies as, "A type of onsite sewage treatment and disposal system that excludes the use of aerator pumps and includes no more than one effluent dosing pump with mechanical and moving parts and uses a reactive media to assist in nitrogen removal" (FDOH, 2010). This will be the definition assumed for the remainder of the brief.

## Fundamentals—Nitrogen Cycle

Nitrogen is ubiquitous in our environment—about 78% of the air around us is made up of nitrogen gas ($N_2$). Nitrogen is an essential element of DNA and RNA and therefore, fundamental to life. The two forms found in the environment are inorganic nitrogen and organic nitrogen; it also exists in many different oxidation states. There is a natural cycle of nitrogen throughout the environment and different processes dictate which form and species it is found. These five processes are nitrogen fixation, nitrogen uptake, nitrogen mineralization (ammonification), nitrification and denitrification. The majority of these biologically processes involving bacteria and are therefore influenced by environmental factors that regulate bacterial growth and survival (e.g. temperature, pH, nutrient availability and moisture) (Hazen and Sawyer, 2009c).

For the removal/reduction of nitrogen in wastewater, the most important of these processes are ammonification, nitrification and denitrification; Equation 1 shows the overall result of these processes. Ammonification occurs when organic nitrogen (usually from urea and proteins) is hydrolyzed into inorganic nitrogen as ammonia, which is then volatized into ammonium ions. Ammonium either is taken up by plants or undergoes nitrification.

$$\text{Organic N} \rightarrow NH4+ \rightarrow NO2- \rightarrow NO3- \rightarrow N2 \qquad \textbf{Equation 1}$$

***Nitrification***

During nitrification, ammonia biologically oxidized into nitrate by nitrifying organisims (bacteria and archaea) such as *Nitrosomonas* and *Nitrobacter*. This is a two-step process, but because nitrite is almost immediately transformed into nitrate it is not considered a product and only an intermediate. As can be seen in Equation 2, nitrification requires oxygen and therefore an aerobic environment. In order to keep the nitrifying bacteria active and to have complete nitrification, the pH needs to be buffered due to the excess hydrogen ions formed and the ensuing acidic environment created during this conversion. Unlike ammonium, nitrate is very mobile and stable and can remain unchanged in the environment unless denitrified.

$$NH_4^+ + O_2 \rightarrow NO_2^- + O_2 \rightarrow NO_3^- \qquad \textbf{Equation 2}$$

***Denitrification***

Denitrification is the only process that actually removes nitrogen from ecosystems and involves the conversion of nitrate to nitrogen gas, as shown in Equation 3. Denitrification can occur through two known biological processes; and it is likely that a combination of these occur in nature depending on what environmental conditions are present (i.e. anoxic or aerobic environment, available electron donors). The first involves heterotrophic and autotrophic bacteria under anoxic (no free oxygen) conditions, requires an electron donor/carbon source and electron receptor. The main difference between the two is the electron receptor, heterotrophs use organic carbon (from the breakdown of organic matter) and autotrophs use inorganic compounds like sulfur, iron, and hydrogen. Recognized only recently, the other process, Anammox (*an*aerobic *amm*onium *ox*idation), involves the partial oxidation of ammonium into nitrite (via *Nitrosomonas sp.*) and then converts the remaining ammonium directly into nitrogen gas by Anammox bacteria. This process does not require organic carbon because ammonium is the electron donor and nitrite the electron acceptor.

$$5CH_2O + 4NO_3^- + 4H^+ \rightarrow 5CO_2\ 2N_2 + 7H_2O \qquad \textbf{Equation 3}$$

## Onsite Sewage Treatment and Disposal Systems

There are 2.6 million onsite sewage treatment and disposal systems (OSTDS) in operation in Florida, which accounts for approximately 1/3 of domestic wastewater treatment (FDOH, 2010).

***Components***

Conventional OSTDS (Fig.1) consist of four basic components 1) pipes 2) septic tank 3) drainfield 4) soil. Piping from the source (usually a home) carries sewage effluent to a septic tank for storage and separation of the sludge and scum, piping out of the septic tank transports septic tank effluent (STE) to an optional distribution tank and then to perforated pipes over the drainfield where it percolates

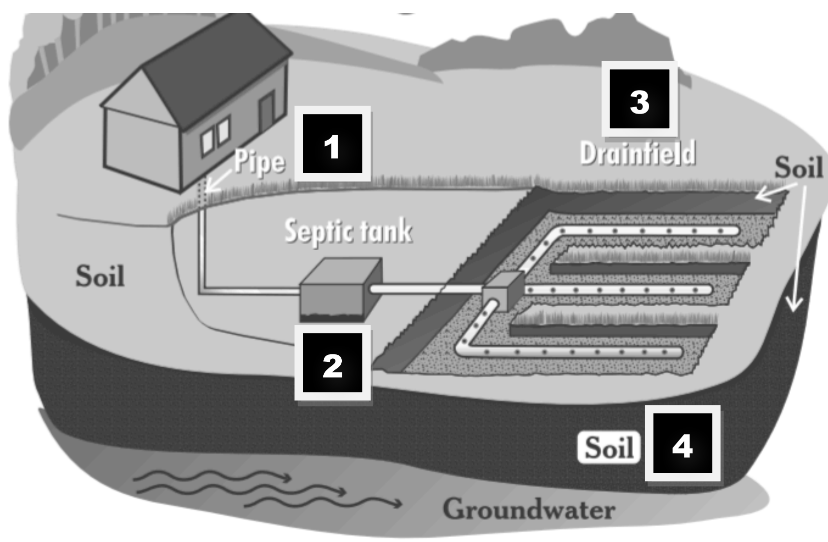



**Figure 1. Conventional onsite sewage treatment and disposal systems.** Reprinted with permission from US EPA, 2003.

into the soil for further treatment (US EPA, 2003).

## Nitrogen Reducing Technologies and Practices

The identification of four main types of technologies/methods that reduce nitrogen from OSTDS resulted from a literature review performed in accordance with the FDOH study's tasks: 1) source separation 2) biological processes 3) physical/chemical processes and 4) natural systems.

Source separation and treatment are emerging as promising technologies of the future, but there is currently little information regarding their long-term effectiveness and acceptance. Physical/chemical processes have historically not been used for OSTDS due to their increased costs and maintenance. Biological processes and natural systems have many similarities and are currently the most frequently used methods of nitrogen removal for OSTDS. Biological processes have been identified as the most efficient for achieving nitrogen reduction and can more easily be adapted to OSTDS than natural systems. All technologies/methods will be briefly discussed below.

## Source Separation

Source separation methods include urine recovery and wastes separation. These methods can sometimes be difficult to implement in existing systems, especially if the homeowners are unwilling to adapt their behavior, but should be considered as sustainable solutions in new developments.

***Urine Recovery***

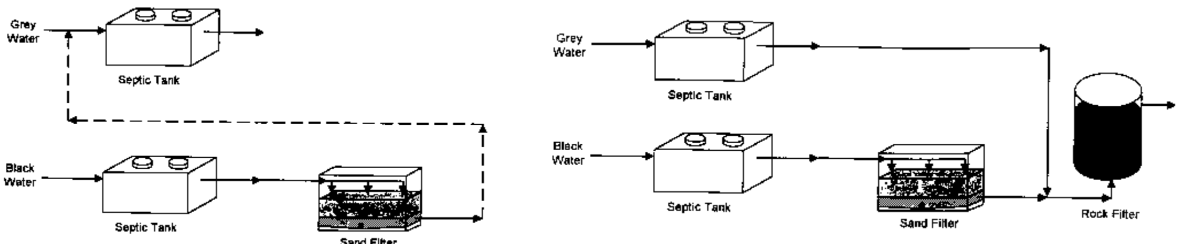
**Figure 2. NoMix urine diversion toilet.** Reprinted with permission from Wc DUBBLETTEN, 2010.

About 88% of total nitrogen in wastewater is due to human urine, which makes source separation an ideal place for nitrogen reduction to occur (World Health Organization (WHO), 2002). Wilsenach (2006) estimated that if only half this urine could be removed prior to wastewater treatment then nearly all the remaining nitrogen in wastewater could be removed. The only way to accomplish urine recovery is to install a urine separating or diversion toilet; one popular name brand is NoMix (Figure 2) (George, 2009). This type toilet enables the separation of blackwater into urine ("yellow water") and fecal waste. The urine can then be used as fertilizer, as is currently done in Sweden and China and historically in the United States. The "brown water" can also be stored or composted and eventually used as fertilizer or treated via conventional septic system or taken offsite for further treatment. Urine diversion toilets also decrease the amount of toilet water used by about 80% (George, 2009). They are not very common in the United States with fewer than 100 being imported for use, but nearly 135, 000 are currently in operation in Sweden; they are also growing in acceptance in Europe.

***Wastes Separation***

Wastes separation is achieved by separating domestic wastewater plumbing by source, greywater and blackwater. Some of the advantages of separating grey from blackwater is that greywater can be reused as toilet water or with minimal treatment used for onsite irrigation. Either Blackwater can undergo primary treatment and then be combined with greywater, or it can be composted, incinerated, or stored in a holding tank and hauled offsite for treatment (Hazen and Sawyer, 2009b). Figure 3 below shows examples of two different treatment options for waste separation.

**Figure 3. Separated Grey and Blackwater Denitrification**. Reprinted with permission from City of Austin, 1995.




**asses through ed with grey**

**Figure 3b. Black water is sand filtered and both grey a black water pass through anoxic rock filter**

As can be seen in Figure 3, grey and blackwater are piped into separate septic tanks where blackwater is sand filtered and can be recycled back into the greywater septic tank (Figure 3a) or both grey and blackwater effluent can be combined before anoxic rock filter treatment (Figure 3b) (City of Austin, 1995).

## Biological Nitrification/Denitrification

Biological processes are the most common form of wastewater treatment. They are subdivided into mixed biomass (one-stage) and segregated biomass (two-stage) depending on if the bacteria for nitrification and denitrification are mixed in one reactor or segregated into separate reactors.

***Mixed Biomass***

Mixed biomass relies on influent wastewater and bacterial cells as the carbon source (electron donor). The limiting step of the single stage process is the amount of organic carbon reaching the denitrification stage. As can be seen in Table 1, recycling nitrified wastewater back to the septic influent improves total nitrogen removal. Examples of mixed biomass processes are suspended growth (extended aeration, pulse aeration and sequencing batch reactors), fixed film,

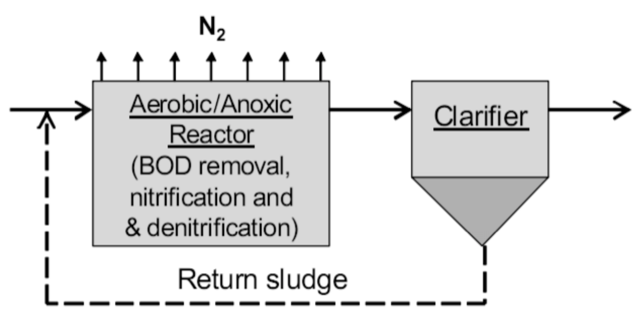



**Figure 4. Mixed biomass with alternating oxic/anoxic reactor**. Reprinted with permission from Hazen and Sawyer, 2009c.

and integrated fixed film activated sludge.

Mixed biomass processes with alternating aerobic/anoxic environments (simultaneous) (Figure 4) uses one reactor that alternates between aerobic and anoxic conditions to achieve both nitrification and denitrification. To create the anoxic environment, aeration is suspended and the heterotrophs deplete the oxygen creating anoxic conditions for denitrification to occur.

**Table 1. Biological Denitrification Processes and Typical Nitrogen Reduction Limits of OSTDS**. Reprinted with permission from FDOH, 2010.

| Biological Denitrification Processes and Typical Nitrogen Reduction Limits of OSTDS | | | |
|---|---|---|---|
| **Process** | **Mixed Biomass (Simultaneous)** | **Mixed Biomass (with Recycle)** | **Segregated Biomass (Two Stage)** |
| **Electron Donor** | Organic carbon from bacterial cells | Organic carbon from influent wastewater | External electron donor (Organic carbon; Lignocellulose; Sulfur; Iron, Other) |
| **Typical N Reductions** | 40 to 65% | 45 to 75% | 70 – 96% |
| **Typical Technologies** | • Extended aeration<br>• Pulse aeration<br>• Recirculating media filters<br>• Sequencing batch reactors<br>• Reciprocating media beds<br>• Membrane bioreactor | • Extended aeration with recycle back to septic tank<br>• Recirculating media beds with recycle back to septic tank<br>• Moving bed bioreactor | • Heterotrophic suspended growth<br>• Heterotrophic packed bed fixed film<br>• Autotrophic packed bed fixed film |

Mixed biomass systems that utilize a recycle loop for increased nitrogen removal (Fig. 5) require two reactors. The first is the septic tank (anoxic), where organic matter is degraded and ammonification occurs; the second is an aerobic reactor, which carries out nitrification. The effluent is separated as it leaves the aerobic reactor, with only a small volume discharged and the majority recycled back to the influent waste stream of the septic tank. This allows the carbon from the degraded organic matter to be utilized as the electron donor in denitrification and helps to buffer the pH of the septic tank reducing the alkalinity requirements (Hazen and Sawyer, 2009c).

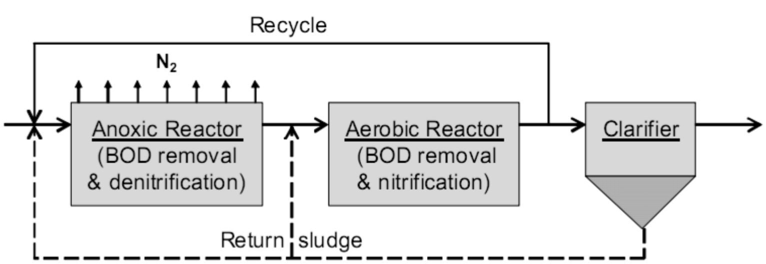



**Figure 5. Mixed biomass recycling denitrification process**. Reprinted with permission from Hazen and Sawyer, 2009c.

Since there is a continuous source of "new" nitrogen in the septic tank and all the effluent from the aerobic reactor is not recycled, complete nitrogen removal is not achieved with this system.

***Segregated biomass***
Segregated biomass systems (Figure 6) separate nitrification from denitrification. In contrast to mixed biomass technologies, which rely solely on organic carbon in the wastewater, segregated biomass systems use alternative sources of organic carbon or elemental chemicals as the electron donor necessary for denitrification (Hazen and Sawyer, 2009b). These technologies often achieve high rates of total nitrogen removal. They require an external carbon source/electron donor, as previously noted, because organic carbon from stage one (nitrification) does not reach stage two (denitrification). Also, stage one may require the addition of a buffer to control alkalinity.

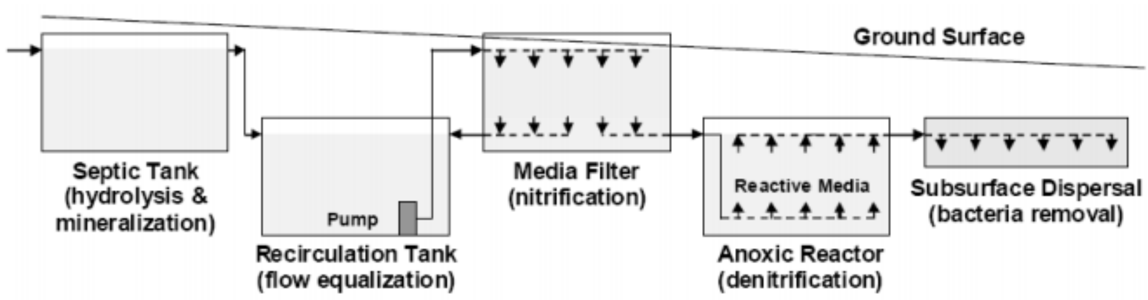



**Figure 6. Passive Two-Stage Denitrification System.** Reprinted with permission from FDOH, 2010.

Either heterotrophic or autotrophic processes are used for denitrification. Heterotrophic processes use solid media as the carbon source including wood chips, sawdust, paper, cardboard, and agricultural residues. Autotrophic processes use solid or liquid media. The most common media for autotrophic processes are sulfur based and many are still under development.

## Chemical/Physical Treatment

Physical/chemical treatment options allow for more control and consistency than processes that rely on biological reactions. They are also more costly and require more attention from the homeowner, making them a less attractive option from a user point of view. In addition, organic nitrogen is not converted into ammonium, as it is in biological processes, making the reduction of nitrogen to very low concentrations difficult (Hazen and Sawyer, 2009c). Examples of physical/chemical treatment options that could be adapted to an OSTDS are membrane separation (reverse osmosis or nanofiltration), ionic exchange, and evaporation (evapotrasnspiration, solar, and distillation).

Membrane separation and ion exchange treatments both have a pretreatment requirement, which is can be very costly and often limits their use to point of use drinking water treatment. Membrane technologies operate via filter separation. Reverse osmosis is the only membrane technology that works to filter out nitrate, but is not commonly adapted for an OSTDS. Membrane bioreactors and immersed membrane bioreactors have been coupled with activated sludge treatment; they do not actually remove the nitrogen and only enhance the biological processes. Ion exchange treatments require regeneration of the exchange sites—this not only adds to the cost but also requires more maintenance and the handling and disposal of potentially hazardous substances.

## Natural Systems

Natural systems utilize a combination of biological, chemical, and physical processes to achieve nitrogen removal. These systems generally rely upon the natural, ecological processes within the receiving environment for passive treatment of STE and as such are inherently passive. A septic system with a drainfield is classified as a natural system because it relies on the characteristics of the soil for nitrification/denitrification/virus removal. Natural systems are attractive because they are simple both operationally and mechanically. The effectiveness of natural systems can vary based on soil characteristics, climate, and method of STE application. The design should be conservative with this unpredictability of environmental conditions in mind. Although the original intent of natural systems was to avoid public exposure to wastes, the design can be adapted for removal of nutrients to avoid groundwater contamination—except for sensitive environments. Examples of this exception are in the Florida Keys where limestone is at the surface, coral reef ecosystems are threatened, and lots are small, and in Wakulla, Leon and Marion Counties in Florida where the protection of spring fed surface waters is a concern (Harden & Chanton, 2010). Types of natural systems that are appropriate include soil infiltration (traditional OSTDS), evapotranspiration/vegetative uptake, and constructed wetlands.

***Soil infiltration***

As long as the appropriate conditions are present in the soil below a drainfield, biological denitrification will occur. These conditions are defined based on heterotrophic denitrification and include 1) the soil's natural drainage, 2) depth to saturated conditions, and 3) the availability of organic carbon (Hazen and Sawyer, 2009c).

The drainage of the soil can give an estimate of its permeability, which will influence the time until saturated conditions occur. Soil must be unsaturated for a certain period to allow for aeration of the soil, which enables the autotrophic bacteria to nitrify ammonium-nitrogen to nitrate—this step is essential and can determine the extent of total nitrogen removal. A shallow water table depth will likely limit the amount of organic matter that can be decomposed due to excess soil moisture and minimum reaeration of the soil. Organic carbon is necessary to heterotrophic denitrification to occur and comes from the breakdown of organic matter. One can see the delicate balance between many environmental conditions that must be necessary for maximum nitrogen removal to occur. Other design features that have been identified to substantially influence the effectiveness of denitrification include the type of pretreatment system and the design of the soil infiltration system—total nitrogen removal varied from 0% in traditional systems to 98% in systems that had low-pressure dosing at grade (Hazen and Sawyer, 2009c).

Table 2 lists important environmental and OSTDS design features influencing nitrogen removal.

**Table 2. Factors influencing nitrogen removal from soil.** Adapted from Hazen and Sawyer, 2009c.

| Environmental Factors | OSTDS Design and Operation Factors |
|---|---|
| Soil<br>• Texture<br>• Structure<br>• Mineralogy | Species of nitrogen discharged to the soil infiltration zone |
| Soil drainage and wetness | Depth and geometry of the infiltrative surface |
| Depth to saturated zone<br>• degree of fluctuation | Daily hydraulic loading<br>• Method of application and frequency |
| Amount of available organic carbon | Density of homes with OSTDS |

***Evapotranspiration and vegetative uptake***
A septic tank would precede either of these systems to remove solids (US EPA, 2002). Lined evapotranspiration beds and vegetative uptake rely on plants to uptake nitrogen and transpire water. The amount of water loss due to evapotranspiration requires that the water be periodically removed because it eventually becomes nutrient rich and has a high salinity (Hazen and Sawyer, 2009c). Plants will need to be replaced occasionally as well. Overall, the performance of these systems is not impressive and would only be appropriate under very specific conditions—which do not typically exist in Florida.

***Constructed wetlands***
Subsurface flow constructed wetlands have been used in conjunction with septic systems and generally consist of a submerged, lined, bed of rocks with wetland vegetation planted at the surface. Although historically thought to remove nitrogen, "wetland plant roots do not supply excess oxygen to nitrify ammonium in septic tank effluent" (Hazen and Sawyer, 2009c). Nearly all nitrate can be denitrified but only about half of the ammonium is transformed to nitrate. Increased nitrogen removal can be accomplished through improved nitrification via the design of vertical beds or recirculation gravel filters (Hazen and Sawyer, 2009c). Anammox is currently being investigated as a means of improving nitrogen removal from wetlands and may be effective since it eliminates the issues associated with denitrification.

## Conclusions and Recommendations

As part of the FOSNR study, two-stage segregated biomass systems (employing either autotrophic (chemical fed) or heterotrophic (carbon fed) denitrification) were selected as the best option to modify existing OSTDS, with future field studies planned to select the best materials to be used for each stage. The selection process was carried out by ranking the technologies on 13 criteria, weighted by comparative significance of each factor, as shown in Table 3.

**Table 3. Ranking criteria and factors for prioritization and classification of passive nitrogen removal technologies in FOSNR study.** Reprinted with permission from FDOH, 2010.

| Ranking Criteria and Weighting Factors | | | |
|---|---|---|---|
| **Criteria** | **Maximum Score S** | **Weighting Factor W** | **Total Possible Score SxW** |
| Effluent Nitrogen Concentration | 5 | 11 | 55 |
| Performance Reliability | 5 | 10 | 50 |
| Performance Consistency | 5 | 9 | 45 |
| Construction Cost | 5 | 7.5 | 37.5 |
| Operation and Maintenance Cost | 5 | 7 | 35 |
| Energy Requirement | 5 | 7 | 35 |
| Construction Complexity | 5 | 5 | 25 |
| Operation Complexity | 5 | 5 | 25 |
| Land Area Required | 5 | 4.5 | 22.5 |
| BOD/TSS Effluent Concentration | 5 | 3.5 | 17.5 |
| Restoration of Performance | 5 | 3.5 | 17.5 |
| System Aesthetics | 5 | 2 | 10 |
| Stage of Technology Development | 5 | 0.5 | 2.5 |
| | | Total: | 377.5 |

There is no one technology discussed above that will be the solution for every site. It is important to remember that the amount of total nitrogen removal necessary will vary by site depending on specific attributes of the location (influent wastewater characteristics, lot size, soil characteristics, existing infrastructure, depth to ground table, background nitrogen concentration, etc.).

Background nitrogen concentrations vary; therefore, the amount of nitrogen removal will be site specific. It is likely that 95% total nitrogen removal is not necessary at each site. Target total nitrogen removal, or nitrogen concentration reaching ground/surface water, should initially be calculated so that the best technology is chosen with this goal in mind. Conservative estimates are necessary because conditions change over time, including loading rates, background concentrations, and soil characteristics. Therefore, routine maintenance and/or inspections may be necessary to ensure the long-term sustainability of these technologies.

## Further Reading

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## Disclaimer

This document was prepared for one of the following two classes at the University of South Florida (Tampa): CGN6933 “Sustainable Development Engineering: Water, Sanitation, Indoor Air, Health” and PHC6301 “Water Pollution and Treatment”.

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