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Nutrient Removal Performance on Domestic Wastewater Treatment Plants (Full Scale System) between Tropical Humid and Cold Climates

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Abstract

Two full scale systems of oxidation ditches for domestic wastewater treatment plants (WWTP) were used as study sites: Phuket Province, southern Thailand (representative of tropical humid climates) and Plum Creek, Castle Rock, Colorado, USA (representative of cold climates). The treatment systems at both sites were designed for biological nutrient removal (BNR) from extended activated sludge. Nitrogen is removed by nitrification-denitrification processes. The solid retention time (SRT) for both treatment plants was ≥ 10 d as recommended by theory for complete nitrification in activated sludge wastewater treatment plants. Influents and effluents from these sites were compared in respect to flow rate, biochemical oxygen demand (BOD), organic nitrogen, ammonium, nitrate, total nitrogen, and phosphorus concentrations. At both sites, nutrient removal reached more than 75 % because there was sufficient carbon for denitrifying and phosphate accumulating organisms. Furthermore, low dissolved oxygen concentration, long SRT, and high temperature could be key factors to promote activity of some groups of bacteria in consuming organic matter and nutrients in wastewater in warm climates. For this reason, plant design and operating procedures for wastewater treatment in cold climates might not be always be applicable to warm climates.

Keywords: Nutrient removal performance; Phuket wastewater treatment; Plum Creek; Castle Rock; Colorado; USA

Introduction

Nitrogen (N) and phosphorus (P) as nutrients contained in domestic wastewater are significant sources of water pollution. For this reason, these nutrients should be removed before they are discharged into the environment. The main concern is that these nutrients trigger eutrophication (algae bloom) in rivers, lakes, estuaries, and oceans. Many nitrogen forms [e.g. ammonia (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-)] can have deleterious effects on aquatic life, human health, and the environment. The public health concern posed by nitrate is methemoglobinemia or blue-baby syndrome. Domestic sewage, agriculture, and industries are all sources of N, but domestic sewage is the major source of this nutrient in Thailand [1]. In order to control excessive discharge of these nutrients, high efficiency treatment systems have been developed; however, these are expensive to build and operate. Removal of both N and P from sewage could use a conventional biological nutrient removal (BNR) method, such as oxidation ditches, extended activated sludge and sequencing batch reactor treatment systems. However, removal of both P and N from wastewater solely with biological treatment is complicated because bacteria do not convert P into a gas phase as they do with N.

The conventional approach for N removal in wastewater involves nitrification from NH_4^+ to NO_2^- on to NO_3^- followed by denitrification from NO_3^- to NO_2^- to nitric oxide (NO) to nitrous oxide (N_2O) and then to as the end product. The process of nitrification followed by denitrification is well-known and widely used for treatment of municipal wastewater. The conventional approach for biological P removal employs phosphate-accumulating organisms to effect anaerobic phosphorus release and aerobic or anoxic phosphorus uptake. P is removed with sludge from the settling clarifier, making it quite difficult to remove phosphorus using biological treatment [2].

Oxidation ditches (OD) are often used for domestic wastewater treatment. However, the OD system can also be used for industrial wastewater treatment. In theory, this treatment system can be designed for removal of organic matter only or both organic matter and nutrients. The OD is a type of extended activated sludge for biological nutrient removal (BNR). The large tank volume providing more than 10 d of solids retention time (SRT) is the key to removal of both organic matter and nutrients. Sufficient capacity is available to accommodate both nitrification and denitrification processes. The OD system combines both anoxic and aerobic zones in a ring or oval-shaped channel. It is equipped with mixing devices in the anoxic zone (denitrification process) and mechanical aeration in the aerobic zone (nitrification process) [3]. Tchobanoglous and co-workers [4] suggested that mechanical aeration/mixing should be used to create a velocity from 0.25-0.30 m sec^{-1} in the channel that is sufficient to keep the activated sludge in suspension. For this reason, the dissolved oxygen (DO) concentration should be decreased and maintained at very low levels to allow denitrification to occur.

The OD system has many advantages, including its capability to remove organic matter and nutrients, consistent processing, quality effluent, simple and easy operation, low energy and chemical demand ability to treat shock loads, and low biosolids production. Disadvantages include the requirement for a large footprint and/or huge structure, needing energy in the aeration tank, and commanding a high initial investment. For these reasons, oxidation ditch treatment systems are not popular in huge cities, (e.g. Bangkok, Thailand) because there is insufficient area to build this system.

The goal of this study was to compare nutrient removal performance from two OD wastewater treatment plants (WWTPs) located in warm and cold climates. The Phuket WWTP was selected to represent a warm climate, while Plum Creek WWTP, Castle Rock, Colorado, USA was chosen to represent cold climates. The biochemical oxygen demand (BOD):N and BOD:P ratios from influent in Phuket and Plum Creek WWTPs were calculated and compared with the theoretical optimum. Also, flow rate, BOD, NH_4^+, NO_3^-, total nitrogen (TN), and total phosphorus (TP) removals from these OD WWTPs were analyzed, compared, and discussed in terms of the design and operation of a biological nutrient removal system.

Materials and methods

1) Phuket municipal wastewater treatment plant, southern Thailand

The Phuket WWTP was selected for study because there is high influent BOD as compared with BOD influent from other centralized WWTPs in Bangkok, Thailand. The average temperature at Phuket WWTP for the whole year is around 30 ºC. The OD in Phuket is capable of removing both organic matter and nutrients significantly. The plant was designed to treat around 28,000 m^3 d^{-1} domestic wastewater.

2) Plum Creek municipal wastewater treatment plant in Castle Rock, Colorado, USA

The Plum Creek WWTP was selected to study because its configuration and operation are similar to the Phuket WWTP except for the anaerobic tank on the front. Conversely, the weather in Colorado is cold in winter and only moderate in summer, so that this site can be used to represent cold climates with an average annual temperature of around 16 ºC. Moreover, in Colorado, there is always a shortage of water. For this reason, the effluent from wastewater treatment could be reused downstream. To facilitate reuse and to protect the environment, both N and P must be removed to very low concentrations. These removal requirements are quite similar to those in Phuket Thailand. The Plum Creek plant was designed to handle domestic wastewater to about 15,200 m^3 d^{-1}.

3) Wastewater treatment sites for study between warm and cold climates

Two OD WWTPs were selected for study: Phuket Province, southern Thailand and Plum Creek, Castle Rock, Colorado, USA. These were selected because of their similar operation, domestic wastewater influent, volume capacity and other design parameters. However, the temperature of water at these WWTPs varied considerably between prevailing conditions in the summer and winter seasons. The performance of DO in anoxic and aerobic zones for both WWTPs was investigated using a DO meter (YSI model: 550A).

4) Quality of influent and effluent of wastewater quality

Influent and effluent wastewater quality was determined for the two WWTPs. Samples were collected every day for one year during 2013 and 2014. All samples were kept at 4°C until analysis. The quality of influent and effluent of wastewater was determined for BOD, NH_4^+, NO_3^-, TN, and TP according to Standard Methods for the Examination of Water and Wastewater 1995 [6]. Mixed liquor suspended solids (MLSS) from both anoxic and aerobic tanks were also analyzed. Temperature and pH were immediately measured in the field. The wastewater quality influent and effluent data from the two treatment plants were used to determine the efficiencies of N and P removal.

Results and discussion

1) Dissolved oxygen concentrations in both anoxic and aerobic zones in the oxidation ditch at Phuket and Plum Creek WWTPs

The operation modes of the DO in both anoxic and aerobic zones in the ODs at Phuket and Plum Creek WWTPs are shown in Figure 1. Plant operators at Phuket and Plum Creek tried to maintain DO in anoxic zone at 0.1±0.05 and 0.3±0.25 mg L^{-1}, respectively. In the aerobic zone the plant operators tried to maintain DO at around 1.2±0.4 and 1.7±0.5 mg L^{-1}, respectively. A higher aeration zone DO was maintained at Plum Creek because this plant used online sensor equipment (including a DO controller, and sensors for oxidation-reduction potential (ORP, NH_4^+, NO_3^-, and pH). The Phuket WWTP plant does not have these tools. The lack of sufficient supplied oxygen could be a significant issue in Phuket WWTP when a high loading enters the plant. Insufficient oxygen would preclude conversion of NH_4^+ to NO_3^-.

2) Design and operational parameters for the oxidation ditch WWTPs in Phuket and Plum Creek

Key design and operational parameters of OD at Phuket and Plum Creek WWTPs are shown in Table 1.

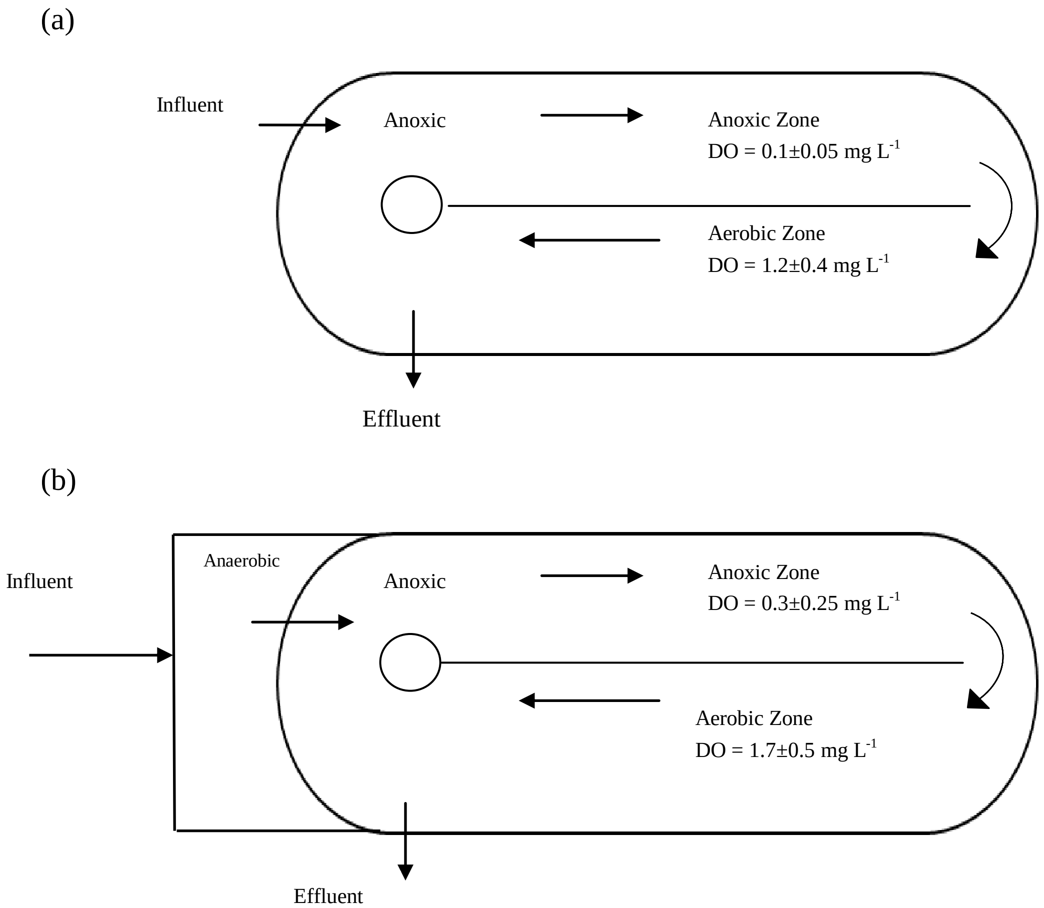

Figure 1 Schematic diagram of point aeration in the oxidation ditch at (a) Phuket and (b) Plum Creek WWTPs.

Table 1 Design and operational parameters for the oxidation ditch WWTPs in Phuket and Plum Creek

Parameter	Phuket			Plum Creek		
	Aerobic	**Anoxic**	**Anaerobic**	**Aerobic**	**Anoxic**	**Anaerobic**
HRT* (h)	24	24	-	19	5.7	1-2
SRT (d)	15	15	-	12.3	3.7	-
DO (mg L^{-1})	1.2±0.4	0.1±0.05	-	1.7±0.5	0.3±0.25	-

* HRT = hydraulic retention time

Tchobanoglous et al. [4] recommended that the SRT should be ≥ 10 d in the aerobic zone of the oxidation ditch to ensure complete nitrification. For this reason, both plants were operated with SRT ≥ 10 d. The Phuket WWTP was operated to provide sufficient total SRTs (30 d) for both anoxic and aerobic zones including recirculation plus recycle flow in order to completely convert the NH_4^+ to NO_3^- in the aerobic zone.

3) Wastewater characteristics at the Phuket and Plum Creek WWTPs

Physical, chemical, and BOD, organic nitrogen, NH_4^+, NO_3^-, TN, and TP characteristics of influent and effluent at the Phuket and Plum Creek WWTPs are shown in Table 2.

Several factors may contribute to the low influent BOD to the Phuket plant as compared with the influent BOD to Plum Creek. First, each house, hotel, condominium or apartment in Phuket has a primary treatment system (such as septic tank or grease trap). Theoretically, septic systems are able to remove some 40-50 % of organic matter and BOD [2, 7]. Second, high wastewater temperatures may increase bacterial activity in sewage pipes. Third, infiltration and inflow could dilute the sewage. Finally, there are no food and garbage disposals to be dumped in wastewater.

4) Nitrogen and phosphorus removal performance

High efficiencies of N and P removals in Phuket and Plum Creek WWTPs were found because of high influent ratios of BOD:N and BOD:P. In other words, there were sufficient sources or carbon for the denitrification and phosphate accumulating organisms (PAOs). Nutrient removal efficiencies are shown in Table 3. Theoretically, appropriate BOD:N and BOD:P ratios for BNR should be higher than 4 [4, 8]. The influent ratios of BOD:N in Phuket and Plum Creek WWTPs were 6.9 and 6, respectively. The influent ratios of BOD:P in Phuket and Plum Creek WWTPs were 48.3 and 48, respectively.

Table 2 Characteristics of the oxidation ditch systems at the WWTPs in Phuket and Plum Creek (average value in 2013)

Parameters	WWTP	
	Phuket	**Plum Creek**
Flow rate (m^3 d^{-1})	28,735	15,160
Temp. (ºC)	30	16
pH	7.2	6.7
BOD_{inf} (mg L^{-1})	174	336
$BOD_{eff.}$ (mg L^{-1})	3.7	3.7
$NH_4^+{}_{inf}$ (mg N L^{-1})	15.9	35.8
TN_{inf} (mg N L^{-1})	25.3	56
$NH_4^+{}_{eff}$ (mg N L^{-1})	8.7	0.7
$NO_3^-{}_{eff}$ (mg N L^{-1})	3.2	3.2
MLSS (mg L^{-1})	7,180	2,330
TP_{inf} (mg P L^{-1})	3.6	7
TP_{eff} (mg P L^{-1})	0.9	0.3
Organic loading rates (kg d^{-1})	5,000	5,094

The N removal efficiency in Phuket WWTP was about 10-20 % lower than in Plum Creek WWTP. Also, P removal in Phuket WWTP was 22-24 % lower than in Plum Creek WWTP.

The recycle ratio of sludge, SRT, HRT, oxygen concentration, and temperature are possible factors affecting both N and P removal efficiencies in these WWTPs. Longer SRT (15 d in aerobic tank and another 15 d in anoxic tank) and HRT (24 d) were operated at Phuket WWTP. Oxygen concentrations in the aeration tank of Phuket WWTP (1.2 mg L^{-1}) were lower than in Plum Creek WWTP (1.7 mg L^{-1}). Maintaining sufficient oxygen concentrations for nitrifying bacteria in aerobic zone (by using DO probe and DO controller) at Plum Creek is thought to be the main factor to account for high N removal efficiency at the Plum Creek WWTP. Occasional insufficient supplied oxygen for aerobic nitrification is the likely explanation for incomplete NH_4^+ removal in Phuket WWTP (see Table 2 and Figure 1). The Plum Creek WWTP performance is consistent with an SRT ≥ 10 d, high recirculation plus recycle flows and sufficient oxygen to provide for complete nitrification and TN removal of > 90 %. The sufficient recycle ratio would bring more NO_3^- as electron donor from aerobic tank to anoxic tank where organic matter can act as an electron donor so NO_3^- can be removed through denitrification. In Phuket WWTP, TN removal is over 70-80 % because this OD system is operated at a sufficient SRT (30 d > 10 d) and recirculation plus recycle flow (because of OD design) to completely convert the NH_3 to NO_3^- in the aerobic zone.

Table 3 Nitrogen and phosphorus removal efficiencies in Phuket and Plum Creek WWTPs in 2013 (average ± SD)

WWTPs	Influent		Effluent		N removal efficiency	P removal efficiency
	TN (mg N L^{-1})	TP (mg P L^{-1})	TN (mg N L^{-1})	TP (mg P L^{-1})		
Phuket	25.3±0.5	3.6±0.4	8.7±4.7	0.95±0.05	70-80%	72-75%
Plum Creek	56±5.5	7±1	7.1±2.8	0.28±0.07	80-90%	96-97%

The mechanism of P removal by biological P-removal (bio P) is totally different as the mechanism of N removal by biological N-removal (nitrifying and denitrifying bacteria). Nitrifying bacteria can change NH_4^+ to NO_3^- and denitrifying bacteria can change NO_3^- to N_2 gas. Bio P could not change P into a gas phase as denitrifying bacteria could with N. The mechanism P removal by bio P would be complicated and taken time. Two conditions (anaerobic and aerobic) are required for bio P to remove P. First, under anaerobic conditions, bio P could release of significant amounts of P from the cell and then quickly change to aerobic conditions. Second, under aerobic conditions, bio P could take significant amounts of P into the cell. Later, the excess bio P sludge from secondary clarifier would be removed. The Plum Creek WWTP features an anaerobic tank on the front, which is not present at the Phuket WWTP (see Table 1 and Figure 1). For this reason, P removal efficiency at the Plum Creek WWTP was higher than at the Phuket WWTP. However, if the bio P sludge is kept too long in the secondary clarifier, P from bio P (inside the cell) could be released, significantly increasing P concentration in the effluent.

Despite varying operating conditions in Phuket WWTP, such as a lower DO in the aerobic zone, longer SRT and higher temperature, nutrient removal at Phuket WWTP does not differ significantly from Plum Creek WWTP. Some of the common oxidizing bacteria could become acclimated, thus more active, at lower DO concentration, long SRT and high temperatures. It is noteworthy that Sinthusith et al. [9] identified a group of ammonia-oxidizing archaea (AOA) in Phuket WWTP but not at Plum Creek WWTP. Furthermore, Limpiyakorn et al. [10] also found an abundance of AOA in WWTPs in Bangkok. Almost all centralized WWTPs in Bangkok are operated at quite low DO in the aerobic zone and wastewater temperatures in these plants were significantly higher than at Plum Creek WWTP. The findings of this study suggest that AOA activity contributes to N removal efficiency at Phuket.

The Phuket facility offers a good example of a WWTP in a tropical humid climate that can significantly remove both N and P. In the influents to most warm climate WWTPs, carbon sources offer insufficient BOD concentrations to support denitrification processes. For example, influents to most WWTPs in Bangkok have very low BODs (30-50 mg L^{-1}), resulting in incomplete N and P removal [11]. It is common in warm climates for BOD in domestic wastewater to be quickly digested in the sewage pipe because the bacteria are so active at higher temperatures, and the sewage piping from the point source to WWTP is very long.

The Plum Creek WWTP is a good representative of a cold climate facility because it can significantly remove NH_4^+. Levels of NH_4^+ in the effluent at this WWTP are quite low (0.7 mg N L^{-1}). In most cold climate WWTPs, low temperature can affect the nitrification process because ammonium oxidizing bacteria (AOB) cannot oxidize NH_4^+ to NO_2^- efficiently. AOB oxidize NH_4^+ to NO_2^- well at higher temperatures (around 30 ºC) [4]. However, in Plum Creek there is sufficient oxygen to promote complete nitrification.

Conclusion

This study confirms that if the influent ratios of BOD:N and BOD:P at the municipal WWTP are higher than 4 and 30, respectively, both N and P was removed sufficiently under optimal plant operating conditions. The activity of some bacteria in warm climate can be promoted in surviving conditions such as low DO in the aerobic zone, longer SRT and high temperatures. Further studies are needed to specify design parameters and operating conditions for warm climate WWTPs because many groups of bacteria can survive at higher temperature and could promote different nutrient removal efficiencies.

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