International Journal of Sustainable Built Environment (2017) **6**, 351–358

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Gulf Organisation for Research and Development

International Journal of Sustainable Built Environment

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Enhancing nitrogen removal efficiency of domestic wastewater through increased total efficiency in sewage treatment (ITEST) pilot plant in cold climatic regions of Baltic Sea

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Received 2 November 2016; accepted 16 May 2017

Abstract

The temperatures of sewage water were too low in cold climatic regions of Baltic Sea, which resulted in inefficiency of denitrification in sewage treatment process (STP). This is not prescribed to meet the effluent nitrogen levels (<10 mg/l) as per Urban Wastewater Treatment Directive 98/15/EC. In order to improve the denitrification efficiency and the subsequent removal of nitrogen from the municipal wastewater as per the above European Commission guidelines, modified process was formulated with pre-anaerobic and post-aerobic activated sewage treatment processes. The modified process includes the rise in ambient temperature up to 20 ± 2 °C by using heat exchangers in Increased Technology and Efficiency in Sewage Treatment (ITEST) pilot plant at the Swedish Environmental Research Institute (IVL) laboratory. The experiments were conducted with the modified process of sewage water in one line (treatment line (TL)) and the existing process in another line (reference line (RL)) of the pilot plant. The physical (such as Temperature, Suspended solids and Sludge volume) and chemical (ammonium-nitrate (NH_4^+-N), nitrate-nitrogen (NO_3^--N) and total-nitrogen (TN)) parameters were analyzed. The results concluded that the NH_4^+-N, NO_3^--N and TN concentrations of treated waste water were satisfactory with a concentration of <10 mg/l as per the European Directives 98/15/EEC at treatment line as compared to influent and reference lines. The average nitrogenous-compounds' removal efficiencies were 84% and 76% of NH_4^+, 80% and 65% of NO_3^-, 78% and 62% of TN for TL and RL, respectively.

Keywords: Eutrophication; Pre-anaerobic; NH_4^+; NO_3^-; TN

Abbreviations: ITEST, Increased Technology and Efficiency in Sewage Treatment; BMEPC, Baltic Marine Environment Protection Commission; STP, Sewage Treatment Process; TN, Total Nitrogen; HELCOM, Helsinki Commission; HRT, Hydraulic Retention Time; ASP, Activated Sludge Processes; COD, Chemical Oxygen Demand; BOD, Biological Oxygen Demand; DO, Dissolved Oxygen; NH_4^+-N, Ammonium Nitrate; NO_3^- - N, Nitrogen Nitrates; EWM, Electronic Weighing Machine; SV, Sludge Volume; SVI, Sludge Volume Index; AN, Ammonium Nitrate; RL, Reference Line; NN, Nitrogen Nitrate; TL, Treatment Line.

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Peer review under responsibility of The Gulf Organisation for Research and Development.

http://dx.doi.org/10.1016/j.ijsbe.2017.05.002
2212-6090/

1. Introduction

The Eutrophication problem punctuated specially in the Baltic Sea is mainly caused due to different man made anthropogenic activities and discharging highly concentrated nitrogenous compounds via agricultural runoff and inadequately treated wastewater in its catchment area into sea (Dupas et al., 2015; Fleming-Lehtinen et al., 2015; HELCOM, 2010). Overloading of nutrients such as nitrogenous and phosphorus compounds to fresh water bodies induces severe problems such as water pollution, eutrophication and development of toxic cyanobacterial blooms, hypoxia and toxic aquatic species (Zhao et al., 2015; Wen et al., 2015; Keidrzynska et al., 2014). Baltic Marine Environment Protection Commission (BMEPC) called 'Helsinki Commission/HELCOM' (formed by Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden) aimed to protect marine environment of Baltic Sea, which is an active organization since last four decades. The self purification of sea was very slow and it was not enough to meet present loading rates of pollutants due to long water retention time to take movement from south to north. This problem was recognized at its implementation level during 1950 (Elmgren, 2001; Lehtinen et al., 2015). Generally, the sewage treatment plants of inter Baltic Sea territory continents as a point source contribute above 30% of nitrogenous compounds' accumulation due to inefficient treatment (HELCOM, 2010).

Biological sewage treatment by activated sludge process has been utilized to resolve problems associated with the water pollution (such as organic materials, nitrogen and phosphorous) for more than one hundred years and still emphasizes that domestic wastewater is the prominent source behind agricultural runoff contribution for eutrophication around the globe (Matuska et al., 2010). Biologically, activated sewage treatment processes (STPs) without pre-anoxic zone were poor in mean total nitrogen (TN) and phosphorus removal rates of 47% and 0%, respectively. However, pre-anoxic zone had better removal rates of TN and phosphorus of 75% and 98%, respectively (Zeng et al., 2011). HELCOM, 2005 (2005) reported that the weekly loading rates of ammonia had decreasing trends but Nitrate has high variation in trends with small changes in temperatures.

Nitrogen removal from activated biological STPs with pre-anaerobic and post-aerobic treatment is the most cost-effective, less sludge production, efficient nutrient removal, high operational flexible and less operational complex process. This process mainly involves anoxic denitrification and aerobic nitrification to convert ammonium to nitrogen gas as compared to other STPs (Kassab et al., 2010; Yao et al., 2013a,b; Zhang et al., 2014; Ruiz et al., 2006). The implementation of biological treatment process temperature is an important factor because enzyme's activity and growth rate are affected in cold countries' environment due to the low temperature (Yao et al., 2013a,b; Sen et al., 1992). It is a challenging and most difficult process especially in winter seasons due to the fall of temperatures less than 5 °C, where nitrification process ceases (Gerardi, 2002). Denitrification stage is not so affected by temperature (Obaja et al., 2003) as compared with nitrification, which is very sensitive to small changes in temperatures between 10 and 17 °C (Randall et al., 1990). For the effective biological treatment and optimum nutrients' removal, the suitable temperatures are 20 ± 2 °C (Yang et al., 2014).

Integrated continuous anaerobic and aerobic treatments at ambient temperature were highly beneficial with reduced hydraulic retention time (HRT) for treating and eliminating sludge through organic degradation. The absence of oxygen environment with limited carbon source (0.3–0.5 mg/l) was sufficient and more efficient, which removes chemical oxygen demand (COD) and biological oxygen demand (BOD) (Hussein et al., 2014; Zeng et al., 2011). Conventional and traditional treatment processes can be replaced by employing combination of activated STPs and ASR for efficient removal of pollutants in sewage water (Zeng et al., 2010).

2. Materials and methods

2.1. Pilot plant location

The ITEST pilot plant, a pilot test facility (www.sjostadsverket.se) center for municipal wastewater purification was located at Hammarby Sjöstadsverk, Stockholm, Sweden. The sewage received by the pilot plant was same as main full scale municipal wastewater treatment plant. The pilot plant shared the pre-clarification (grid and sand trap), pre-sedimentation and phosphorous precipitation with the full scale main treatment plant. The layout and schematic view of ITEST pilot plant with treated line is shown in Fig. 1. It is worth to mention that the layout of reference line was the same as treated line except for the absence of heat exchangers (Fig. 1)

2.2. Description pilot plant and parameters

The pilot plant was equipped with two identically activated sludge recycling (ASR) processes. One with modified treatment temperature and another is same as main water treatment plant (i.e. reference line temperature). Bacteriological nitrification and denitrification are recognized as feasible processes for removal of nitrogen from wastewater. The relationship between treatment temperature and reaction rate is an important parameter for the design consideration particularly in cold climate (Dawson and Murphy, 1972). One of the test lines was run at sludge concentration, sludge age and temperature similar to the main Activated Sludge Processes (ASP) treatment plant, which is named as reference line (RL). Another line was run at same sludge concentration and sludge age with a desired temperature of about 20 °C, named as treatment line (TL). Heat exchanger was used for treatment line after the primary

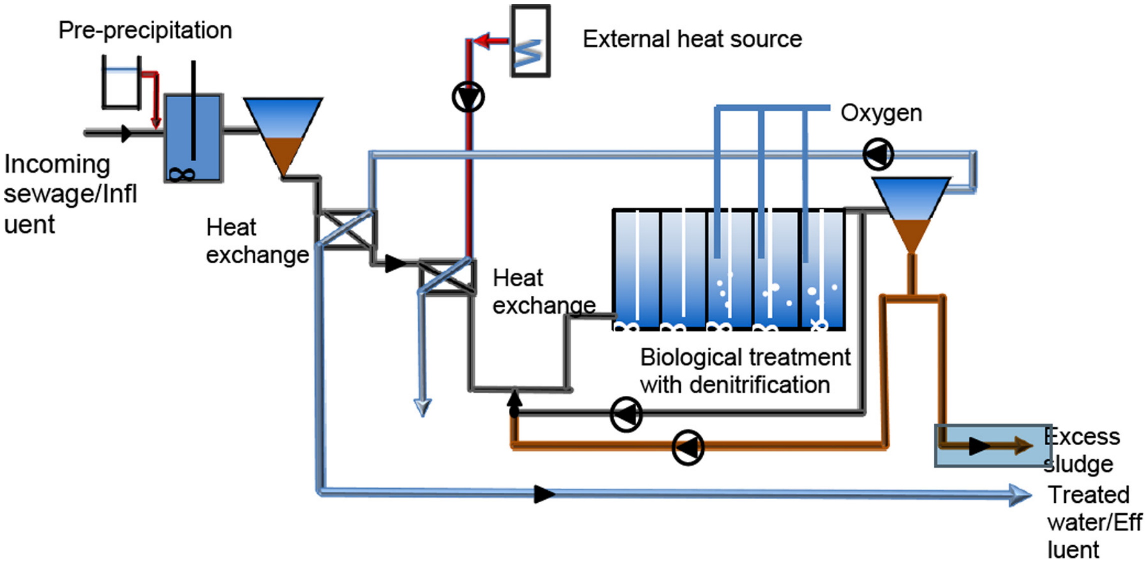

Fig. 1. ITEST pilot plant design with treatment line provided along heat exchanger to maintain 20 ± 2 °C in the activated sludge zone.

clarifier to increase influent sewage temperature based on the simulation of incoming influent temperatures (Fig. 1). Pre-sedimentation tank was equipped with coarse screens and sand trap instruments. Common phosphorus per participation was also included at main STP level, where the influent wastewater reached before the primary clarifier of pilot plant. Pilot plant's two lines were made with automated influent flow rate adjustment, which have similar hydraulic loading as main/actual ASP treatment plant with respect to time.

The pilot project was adopted with two steps of bacteriological pre-denitrification (anaerobic/anoxic) and post-nitrification (aerobic) to accomplish the activated sewage treatment, in which, the enhanced nitrogen removal could be achieved with returned activated sludge from an aerobic zone to the anoxic zone through clarifier (Metcalf and Eddy, 2003). Both the treatment lines consist of five tanks/chambers: first two (1st and 2nd) for denitrification step with restricted oxygen supply and next three (3rd, 4th and 5th) for nitrification step with sufficient oxygen supply. Both the treatment lines along with the 5 chambers of pilot plant are shown in Fig. 1.

2.3. Plant operational and observed parameters

The pilot plant was operated at a wastewater influent flow rate of 0.5 m^3/hr/line and 8 h of hydraulic retention time (HRT). Agitators were assembled to each and every reactor of both the lines to obtain good mixing of sewage in anaerobic chambers and sewage as well as air in aerobic chambers. Aeration was provided with pressurized air passing through the air probes in nitrification/aerobic chambers to make sure that there are enough dissolved oxygen levels of nitrification in initial 3rd reactor (2.5 mg/l) and in terminal 5th (2.0 mg/l) reactor. Each reactor of both the lines was equipped with pH reading meter probes to make sure that the process ranged from 6.5 to 7 (pH). Denitrification reactor was facilitated with recirculation of activated sludge from 5th reactor (remnant nitrification reactor) to 1st reactor (initial denitrification reactor) at a flow rate of 2.0 m^3/hr, which is 4 times higher than the influent flow rate. Several reports supported the evidence that nitrification was inhibited by insufficient dissolved oxygen (DO) (Guo et al., 2013; Sen et al., 1992). Online monitoring system was facilitated for DO and pH continuously throughout the process and calibrated every week based on recommendations from manufacturer with respect to treated water analysis.

2.4. Sample collection

The influent and effluent samples were collected for RL, TL and incoming sewage using continuous sampling system with 10 ml collection capacity for every six minutes throughout the week. DO and pH were also measured using portable instruments for processes' calibration and samples were tested for processes as well as nitrogen removal efficiency evaluation.

2.5. Ammonium nitrate, nitrogen nitrate and total nitrogen estimation

Ammonium nitrate (NH_4^+-N), nitrogen nitrates (NO_3^--N), and total nitrogen (TN) were measured for TL and RL using the Dr. Lange analysis cuvette kit. Cuvettes were pre-papered solutions for analyzing different readable ranges of NH_4^+-N, NO_3^--N and TN, which are given in (Table. 1). Mechanical pipette was used to add 5–10 ml of collected samples to other reagents of respective cuvette. They were shaken thoroughly and left for 15 min, 15 min and 1.25 h to measure the readings from spectrophotome-

Table 1
Estimation of nitrogen forms with cuvette.

Cuvette labelle No.	Estimated nitrogen form	Readable range (mg/l)
LCK 304	Ammonia nitrogen (NH_4^+-N)	0.015–2.0
LCK 303	Ammonia nitrogen (NH_4^+-N)	2.0–47.0
LCK 339	Nitrate nitrogen (NO_3^- -N)	0.23–13.50
LCK 340	Nitrate nitrogen (NO_3^- -N)	5.0–35.0
LCK 238	Total nitrogen (TN)	5.0–40
LCK 338	Total nitrogen (TN)	20.0–100.0

ter for NH_4^+-N, $NO3^-$-N and TN, respectively as per instructed thumb rules.

2.6. Suspended solids measurement

Suspended solids were measured for TL and RL using filter paper (55 mm diameter and 1.2 micro meter pores size) vacuumed filter and 50 ml sludge sample. According to instruction manual for wastewater treatment plants analysis (VAV, 1984), filter paper was weighed using electronic weighing machine (EWM) and denoted as W_{fp}. Later, vacuum filtrated sludge filter paper was oven dried in an incubator at 105 °C for 24 h and waited until to attain room temperature for measuring suspended solids using EWM and the weight denoted as W_{fps}. The suspended solids (SS) are calculated as follows:

$$SS = ((W_{fp} - W_{fps}) \times 1000)/V \quad (1)$$

where W_{fp} = weight of filter paper (g), W_{fps} = weight of oven dried filter paper and sample (g), and V = volume of the sample filtered (l).

2.7. Sludge volume and sludge volume index

To access the efficiency in activated sludge process, the suspended solids, sludge volume and sludge volume index were analyzed. Sludge volume (SV) was estimated for treatment, reference and main STP lines using standard procedure. A 1000 ml graduated volumetric measuring cylinder was filled with sludge of 5th reactor (terminal nitrification) and left for 30 min to settle and readings were taken. Sludge volume index (SVI) was introduced by Mohlman (1934) and has become the standard to mensurate physical characteristics of activated sludge solids.

SVI is volume in millimeters occupied by 1 gram of suspension after 30 min of settling and used typically to monitor the settling characteristics of activated sludge and other biological suspensions. But sludge volume index is not supported theoretically. SVI (ml/l) was calculated for treatment line and reference line with the following equation:

$$SVI = (SV(ml/l)/MLSS(mg/mg)) \times 1000 \quad (2)$$

where SV = Sludge Volume (ml/l) and MLSS = Mixed Liquor Suspended Solids (mg/mg).

3. Results and discussion

3.1. Effect of temperature on aerobic and anaerobic respiration

Temperature plays an important role to accomplish and efficient nitrogen removal of biological ASR treatment processes. According to the study of Guo et al. 2013, the overall nitrogen removal efficiencies were regulated by denitrification at low temperatures. The experiment was carried between September and April (mid of autumn-winter and mid of spring), to study the nitrogenous compounds' removal efficiencies with respect to temperature. Both the reference and temperature lines' temperatures for the study period (38th week to 17th week) were monitored and depicted in Fig. 2. It is observed that the reference line showed large discrepancy in temperature of about 17 °C and 8 °C during 38th and 52th weeks, respectively.

It is found that the nitrification and denitrification processes were almost ceased at a temperature of 5 ± 2 °C and influent nitrogenous compounds were discharged without decomposition, whereas stabilization of the nitrification and denitrification was accomplished by raising temperature to 20 ± 2 °C (Guo et al., 2013). Therefore, in this study a temperature of 20 ± 2 °C is maintained in treatment line. However, temperatures of treatment line were not constant with small variations from 38th week to 48th week (3rd week of September to 3rd week of November), due to use of plate type heat exchanger. Plate type heat exchanger was unable to maintain desirable temperature of 20 ± 2 °C due to over incoming sewage temperature, there by a difference of 1 to 3 °C temperature was observed in treatment line (Fig. 2). Therefore, the plate type heat exchanger was replaced with spiral-wound heat exchanger (combination of Sondex S4A-1G for first step and Sondex S8A-1G for second step). Then, the treatment line temperature was increased and maintained constantly to desirable level 20 ± 2 °C in short span of time from 50th week onwards (Fig. 2). At this temperature, the overall nitrogen removal efficiencies were increased and able to meet effluent water concentrations of <10 mg/l as per European Directives 98/15/EEC (Figs. 6–8) (Sudarno et al., 2011).

3.2. Nitrogen concentrations and removal efficiency

Ammonium nitrate (AN), Nitrogen nitrate (NN) and Total nitrogen (TN) concentrations of treatment line effluent, reference line effluent and influent were shown in (Figs. 3-5). AN, NN and TN readings were taken in 'mg/l' at a constant interval (on weekly basis). The nitrogenous compounds' (AN, NN and TN) removal performance was more beneficial in treatment line as compared to reference line at biological ASP treatment and stabilized ambient processes' temperature of 20 ± 2 °C.

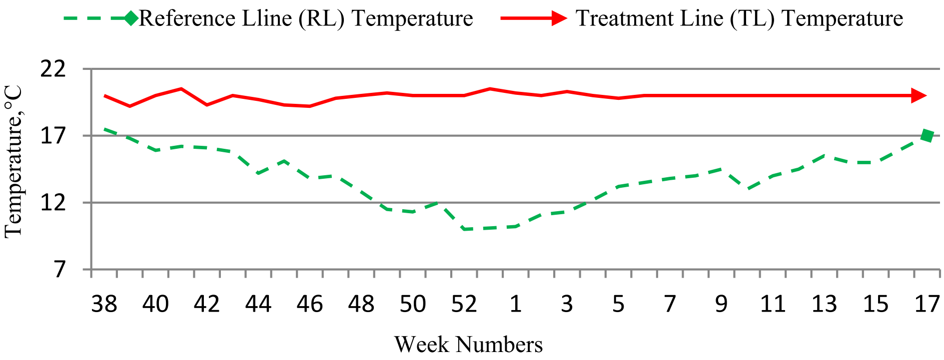

Fig. 2. Temperatures of reference line (RL) and treatment line (TL).

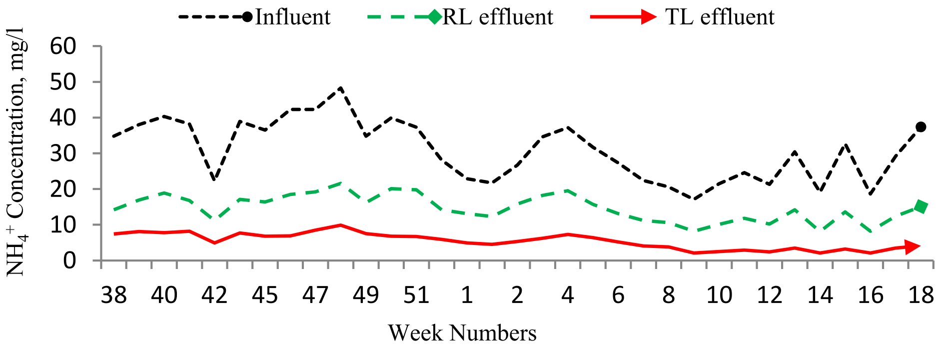

Fig. 3. Ammonium nitrogen concentration of influent and effluents lines (RL and TL).

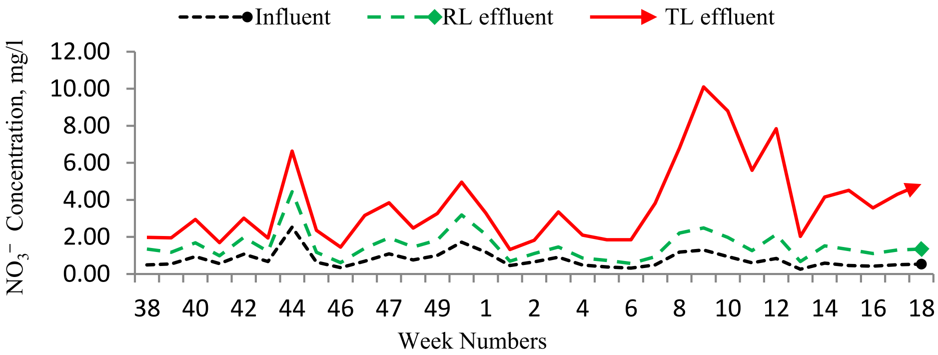

Fig. 4. Nitrogen nitrate concentration of influent and effluents lines (RL and TL).

3.2.1. Ammonium nitrate (NH_4^+-N)

Previous studies indicated that denitrification rate was significantly affected by lower temperatures for biological treatments and denitrification rate at 5 °C was decreased by 10 times linearly as compared to 20 °C (Guo et al., 2013; Choi et al., 1998; Hocaoglu et al., 2011). The concentration of AN (NH_4^+-N) in the influent was measured on an average of 30 mg/l (minimum and maximum was 17 and 48 mg/l) (Fig. 3). The AN concentration (mg/l) was observed as >10 mg/l and <10 mg/l at reference and treatment lines, respectively (Fig. 3). The nitrogenous compounds' concentration of <10 mg/l is recommended as the best for treating sewage water as per European Directives 98/15/EEC.

The NH_4^+-N removal efficiency of 60% in RL and 90% in TL was attained with a difference of 4 °C temperature for both the treatment and reference lines (Fig. 6). After changing the heat exchanger plate, the minimum removal rate was 47% in RL and 75% in TL (Fig. 6). The ammonium ions' concentrations of TL were very low (Fig. 3); it indicates that temperature had great influence on nitrification process removal efficiency.

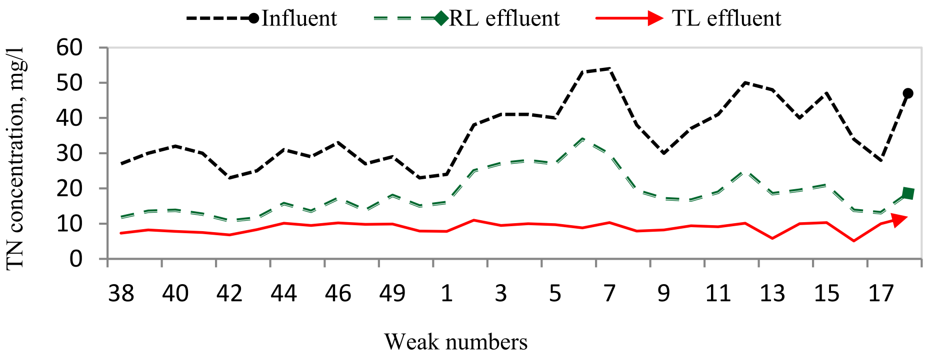

Fig. 5. Total nitrogen concentrations of influent and effluents lines (RL and TL).

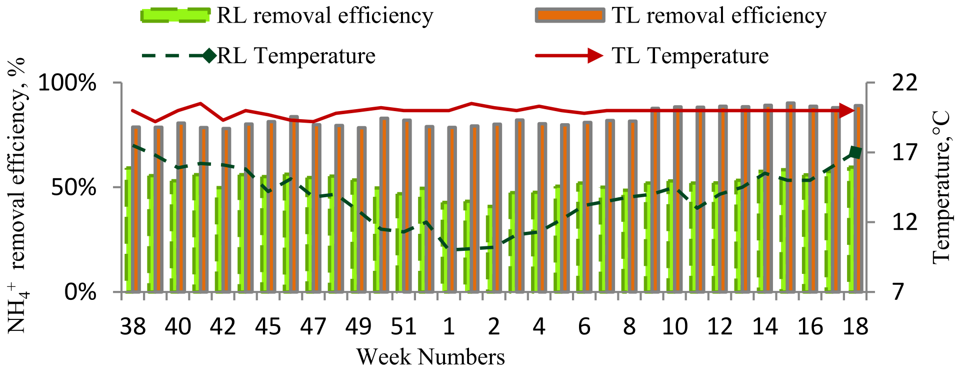

Fig. 6. Ammonium nitrate (NH_4^+) removal efficiency of treatment line (TL) and reference line (RL).

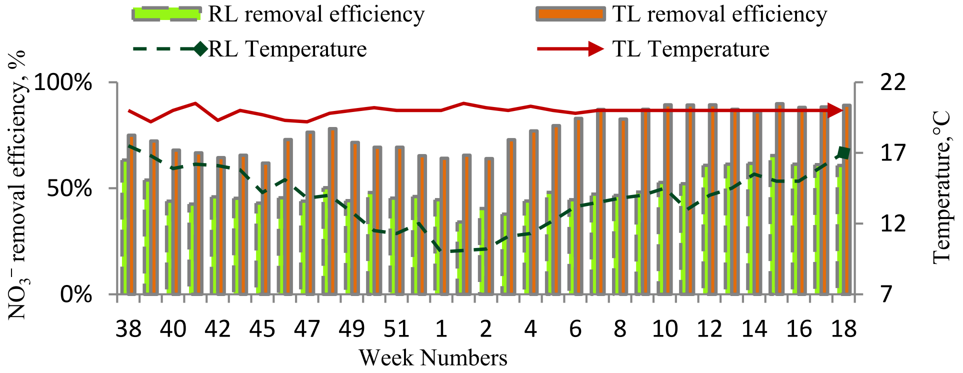

Fig. 7. Nitrogen nitrate (NO_3^-) removal efficiency of treatment line (TL) and reference line (RL).

3.2.2. Nitrogen nitrate (NO_3^--N)

The concentration of NN (NO_3^--N) in influent sewage was recorded on an average of 0.77 mg/l (minimum NN = 0.26 mg/l and maximum NN = 2.53 mg/l) and the maximum and minimum effluent values were 4.4 and 0.57 mg/l and 10.10 and 1.38 mg/l for RL and TL, respectively (Fig. 4). NN removal efficiency of 65% in RL at 17 °C and 90% in TL at 20 °C was observed after stabilizing the processes (Fig. 7). Previous studies' results also punctuated that nitrification rate had different behavioral performance with respect to varying temperatures (Guo et al., 2013). The rapid decrease in nitrification was observed when temperature fell down to 5–10 °C (Hocaoglu et al., 2011) due to inhabitation of nitrifying bacteria. Similar performance of 85% to 90% and 20% to 40% NN removal efficiency was observed at 15 °C and 5–10 °C, respectively (Choi et al., 1998).

3.2.3. Total nitrogen (TN)

Total nitrogen (TN) concentrations were reduced to less than 10 mg/l in effluent of TL after stabilization of process temperature (20 ± 2 °C) whereas effluents of RL had the

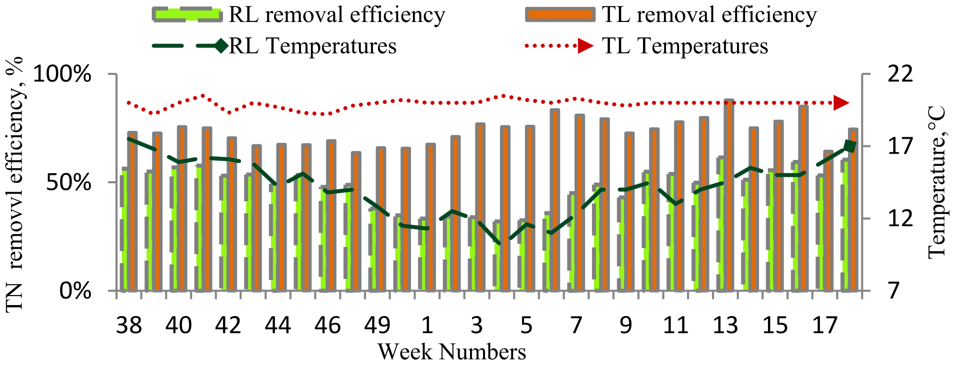

Fig. 8. Total nitrogen (TN) removal efficiency of treatment line (TL) and reference line (RL).

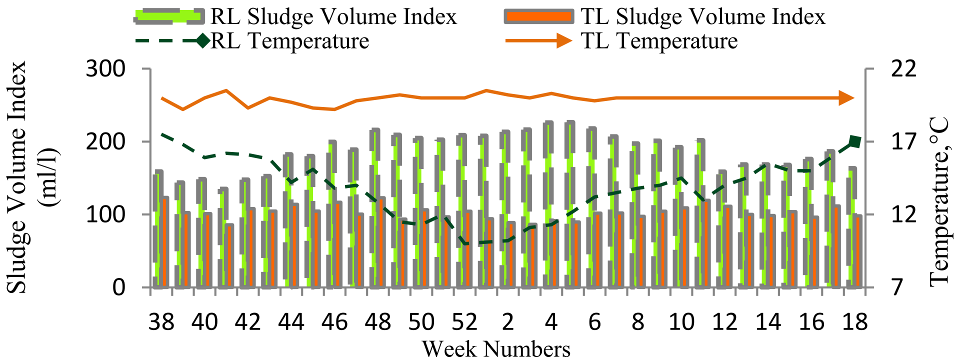

Fig. 9. Comparison of treatment and reference lines sludge volume along with temperatures.

concentration range of 18 to 10 mg/l (Fig. 5). Before stabilization of the processes (temperature of TL from 38th week to 48th week), TN concentration of test results was not satisfactory (ranged between 9and12 mg/l) to meet nitrogen concentration of <10 mg/l as per the directive 98/15/EEC (Fig. 5). Total nitrogen removal efficiency was not significantly affected with a increase/decrease of 2–3 °C processes' temperatures at 20 °C, however if processes' temperature dropped from 20 °C to 10 °C then a rapid decrease in TN removal efficiency was observed (Fig. 8). From 48th to 18th week, TL and RL removal efficiency was 77–88% and 56–61%, respectively with an average temperature difference of 7 to 3 °C (Fig. 8).

3.3. Sludge characteristics

Fig. 9 shows the graphical representation of sludge volume index (SVI) of reference and temperature lines with the temperature for the study period. The minimum and maximum calculated suspended solids (SS) were 2351–3782 mg/l and 2388–4585 mg/l in TL and RL, respectively. Sludge volume (SV) was measured between 380–780 ml/l and 250–380 ml/l for RL and TL, respectively. Using SS and SV, the SVI values for both the reference and temperature lines were computed and are shown in Fig. 9. SVI ranges between 135 and 227 and 86 and 123 for RL and TL, respectively (Fig. 9). Previous studies prove that the SVI range of 50–150 had no effect on sludge characteristics (such as sludge settling and flocculation formation) (Gerardi, 2002; Jenkins et al. 2004; Randall et al. 1990).

4. Conclusions

Nitrification and denitrification were predominantly influenced by temperature in the range of 12–20 °C and discrepancy of nitrogen removal with temperature was very small at 5–10 °C. Enhancement of nitrogenous-compounds' removal efficiency and reduction of sludge production was achieved by maintaining ambient processes' temperature of 20 ± 2 °C and sufficient dissolved oxygen concentration. After the processes' stabilization (from 48th week on words), the average sludge volume and suspended solid production achieved were 320 ml/l and 3000 mg/l for TL and 610 ml/l and 3300 mg/l for RL, respectively. Further, the AN, NN and TN concentrations of treated waste water were satisfactory with a concentration of <10 mg/l as per the European Directives 98/15/EEC at treatment line as compared to influent and reference lines. The average nitrogenous-compounds' removal efficiencies were 84% and 76% of NH_4^+, 80% and 65% of NO_3^-, 78% and 62% of TN for TL and RL, respectively.

Acknowledgements

This study was supported by The Royal Institute of Science and Technology (Kungliga Tekniska hogskolan), Swedish Environmental Research Institute (IVL), Hammarby Sjöstad, Oskarhamn Municipality, Emerson Process Management AB, Jayway Innovation AB, and partly funded by European commission within LIFE$^+$ environment. The authors would like to thank Lars Bengtsson, Swedish Environmental Research Institute for guidance provided throughout the study period.

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