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Alternating Aerobic and Anoxic Conditions to Eliminate Sludge Accumulation in the Oxidation Ditch System

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ABSTRACT

The purpose of the present study is to investigate the performance of an upgraded oxidation ditch (OD) system, which was designed and implemented to solve the problem of sludge accumulation at the bottom as well as to get the best removal efficiency of total nitrogen (TN). The upgrading concept is based on dividing the operating volume of the upgraded OD to achieve interchanging between aerobic and anoxic circumstances in order to provide simultaneous nitrification and denitrification (SND). The obtained results indicated that the average TN removal efficiency was 60%, which could be obtained due to a highly efficient SND approach. In addition, the better TN removal efficiency corresponds to the lower sludge volume index (SVI), which reflects the efficiency of the upgraded OD in preventing the accumulation of sludge at the bottom. Effluent ammonium-nitrogen (NH_4^+-N) and nitrate (NO_3^--N) concentrations corresponding to a minimum SVI of 41.9 mL/g were 8.6 mg/L for NH_4^+-N and 8.6 mg/L for NO_3^--N, respectively. Furthermore, the upgraded OD successfully removes 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and total suspended solids (TSS) below the permissible limit for final effluent of 60, 80, and 50 mg/L respectively.

Keywords: activated sludge, denitrification, nitrification, oxidation ditch, sludge accumulation, upgrade, wastewater treatment

INTRODUCTION

The activated sludge method is used in the oxidation ditches (ODs) system to treat wastewater biologically. The primary benefit of ODs is their ability to produce high-quality effluent at the lowest possible cost because of nitrification and denitrification, it is possible to use only one reactor to remove all carbonaceous BOD_5 (Stensel & Coleman 2000; Liu et al. 2010; Fouad and El-Morsy, 2012; Agbewornu et al., 2021; Gogina and Gulshin, 2021). Long solids retention time (SRT) is applied in the operation of oxidation ditches (ODs). This has low operational needs, produces less sludge, and requires little maintenance while minimizing the impact of shock loads (Hasselkus, 2000; Metcalf & Eddy, 2007; Zhan et al., 2013; Zhang et al., 2019; Agbewornu et al., 2021; Gogina and Gulshin, 2021). A single or multichannel may be configured within a basin that is shaped like a ring, oval, or horseshoe, and aerators may be positioned horizontally or vertically (Chen et al., 2010).

Aeration or mechanical mixing is required to maintain contact between the microbial organisms and the dissolved organic matter. The oxygen needed to support the aerobic biological process can be supplied using mechanical aeration or diffused air. Furthermore, mixing and aeration are promoted by ensuring that the reactor's horizontal velocity is enough to provide the required turbulence. Therefore, the horizontal velocity in the ODs system must be between 0.25 and 0.60 m/s, with a normal range of 0.25 to 0.35 m/s (Metcalf and Eddy, 2007; Fouad and El-Morsy, 2014). Typically, a horizontal velocity of more than 0.25 m/s is recommended to a) provide enough dissolved oxygen (DO) to maintain aerobic conditions; b) prevent the settling of organic and solid particles; and c) evenly mix the wastewater with the suspended biomass, nutrients, and DO (Gillot et al., 2000; Abusam et al., 2002). However, the horizontal velocity is limited to a maximum of 0.60 m/s to prevent excessive erosion, excessive aeration, or excessive recirculation, (Fouad and El-Morsy, 2014).

In general, many problems arise when operating the oxidation ditches (OD) system under the preceding velocity values (Hartley, 2008; Fouad and El-Morsy, 2012). Where sand or grit removal is not provided before the ditches; rather, wastewater is screened and piped straight into the ODs. Moreover, rain-induced erosion causes inorganic particle solids to flow into the OD system, accelerating inorganic solid deposition in sludge due to the lack of the existence of combined sewerage systems and the little attention paid to rainwater flow in some developing countries (Fouad and El-Morsy, 2014; Li et al., 2014). Additionally, grit settling can be accelerated by receiving large quantities of grit during rainy weather, particularly if a combined sewer is involved, or by stormwater that has a high solids concentration. The accumulated layer of sludge as grit and sand particles settle at the bottom of the OD. The oxidation ditch system's best-collected sludge layers can change performance by altering the hydraulics of the ditch due to its small effective volume. It is expected that several problems with removal effectiveness, nitrification, denitrification, sedimentation qualities, etc., may arise if the collected solids are not regularly cleaned. Moreover, the regular cleaning of the reactors has caused a significant increase in operational and maintenance costs (Schipper et al., 2010; Fouad and El-Morsy, 2014).

Biological nitrification and denitrification processes are frequently used in conventional treatment technologies to lower total nitrogen (TN) loading in wastewater (Hartley, 2008; Yan et al., 2019; Wang et al., 2019a; Agbewornu et al., 2021). The system design, wastewater treatment plant (WWTP) loading, operational manner, and aeration control mechanism all influence how well OD removes nitrogen (N). Sequential nitrification under aeration and denitrification under anoxic conditions are used to remove nitrogen from biological systems. Dissolved oxygen (DO) concentration in the OD declines as the channel flow exits the aeration zone until it is depleted, and anoxic zones develop in the ditch where nitrate (NO_3^--N) is employed instead of DO to remove nitrogen (N) (Hasselkus, 2000; Latifa et al., 2010; Zhou et al., 2012; Zhou et al., 2013; Wang et al., 2019b; Raboni et al., 2020; Agbewornu et al., 2021). Hartley (2008) concluded that the best settleability and lowest sludge volume index (SVI) occur at about the same anoxic fraction at the lowest effluent TN, with an ammonium-nitrogen (NH_4^+-N): nitrate (NO_3^--N) ratio of about 1.

The simultaneous nitrification and denitrification (SND) approach represents a set of biological nitrogen removal processes in which there is no longer a need for a separate anoxic compartment because nitrification and denitrification take place simultaneously in one aerated reactor. Therefore, SND is important to TN removal in OD systems (Pochana and Keller, 1999; Ammary and Radaideh, 2005; Yongzhen et al., 2008; Liu et al., 2010; Agbewornu et al., 2021; Gogina and Gulshin, 2021). Studies have indicated that nitrification in activated sludge systems can be completed at low levels of dissolved oxygen (DO) under conditions of low organic loading and long solids retention time (SRT) (Zhao et al., 1999; Gogina and Gulshin, 2021).

The present study intends to investigate the performance of the upgraded oxidation ditch system in Tazmant WWTP, Egypt by dividing the operating volume of the upgraded OD to achieve alternating aerobic and anoxic conditions in order to achieve SND to get the best removal of TN and eliminate the accumulation of sludge inside the bottom of the upgraded OD.

METHODOLOGY

The oxidation ditches before upgrading

Oxidation ditches have been upgraded to solve the problem of sludge accumulation. This problem appeared as shown in Figure 1 in a way that reduces the effective tank size, where it was found that the effectiveness of biological treatment and nitrogen removal had declined. The aeration system was weak to the extent that it negatively affects the quality of biological treatment, in addition to the lack of formatting aerobic and anoxic zones in the surface area of the OD, which is required to control the nitrification and denitrification processes. The quality of treated wastewater decreased significantly before upgrading more than the specifications of treated wastewater according to Metcalf and Eddy (2007) as shown in Table 1. Therefore, a decision was taken to develop the WWTP to solve this problem to meet

Figure 1. Sludge accumulation inside the oxidation ditches

Table 1. The treated wastewater characteristics of Tazmant WWTP before upgrading

Parameter	Effluent (secondary treated wastewater)	Limits for final effluent*
pH	7.9 ± 0.4	6.5–8.5
Temperature (ºC)	24.5 ± 2.8	25–30
BOD_5 (mg/L)	67 ± 6.3	≤60
COD (mg/L)	128 ± 9.8	≤80
TSS (mg/L)	136 ± 12.5	≤50
DO (mg/L)	2.5 ± 0.4	≥4
NH_4^+-N (mg/L)	26.9 ± 3.8	–
NO_3^--N (mg/L)	14.7± 2.7	≤50

Note: * Adapted from Metcalf and Eddy (2007).

the required treatment standards. In this context, it was demonstrated that the majority of the ODs exhibited the same tendencies for sludge accumulation under the same operating parameters irrespective of the efficiency of the grit removal chambers (Fouad and El-Morsy, 2014).

Description of the upgraded wastewater treatment plant

The upgraded wastewater treatment plant (WWTP) shown in Figure 2 receives 70000 m^3/d of municipal wastewater. The WWTP was implemented in Tazmant City, Bani-Sweif Governorate, Egypt. Raw wastewater is first delivered into the grit removal chamber and screens to begin the preliminary treatment. The effluent flows to the oxidation ditches and final sedimentation tanks for secondary treatment. The WWTP was designed to treat sewage with an oxidation ditch system containing five parallel units of oxidation ditches followed by five final sedimentation tanks. Each unit was previously designed to treat 12,500 m^3/d of wastewater, and it has recently been upgraded to treat 14,000 m^3/d of sewage.

The standard installation of air diffusers on oxidation ditches as shown in Figure 3 was part of the upgrading procedure to improve control over the processing of activated sludge.

Wastewater characteristics and operating parameters

From July 2019 to July 2020, the pilot run phase's raw wastewater parameters and operating parameters were collated and statistically analyzed as indicated in Table 2 and Table 3 respectively. All tests were carried out in the Laboratory

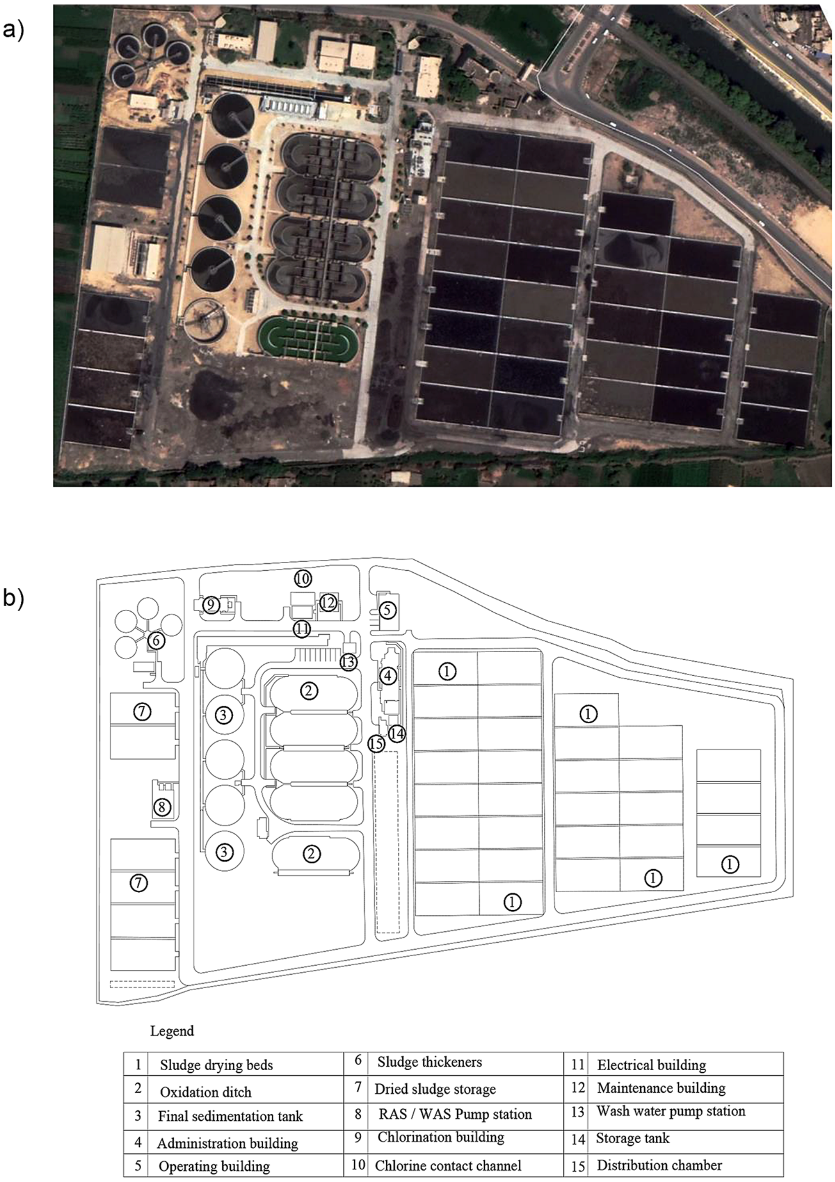

Figure 2. Upgraded Tazmant WWTP in (a) remote sensing technology image adapted from Google Earth, February 2020, (b) a general layout

Table 2. The raw wastewater characteristics of Tazmant WWTP

Parameter	Raw wastewater*
pH	7.3 ± 0.39
Temperature (ºC)	26.42 ± 0.87
BOD_5 (mg/L)	220.1 ± 40.19
COD (mg/L)	447.8 ± 49.51
TSS (mg/L)	197.5 ± 24.4
TN (mg/L)	37.9 ± 4.83
NH_4^+-N (mg/L)	28.4 ± 3.52
DO (mg/L)	4.43 ± 0.95

Note: * Samples of raw sewage were collected after grit removal, and the measurements due to the experimental program were completed within 12 months.

of Tazmant WWTP under the Standard Methods (2017) for the Examination of Water and Wastewater, 23rd edition, prepared and published by APHA, AWWA, and WEF, 2017.

Operating mode

The operating volume of the upgraded OD was roughly evenly divided into the aerobic zone and anoxic zone as shown in Figure 4 so as to achieve alternating aerobic and anoxic conditions within the ODs in order to achieve SND for the best removal of TN and eliminate the accumulation of sludge inside the ODs.

Table 3. The operating conditions of Tazmant WWTP

Parameter	Value	Design criteria*
Aeration period (θ) (hr.)	13.64	20–30
Sludge age (θ_c) (day)	28.7	20–40
Mixed liquor suspended solids (MLSS) (mg/L)	4352 ± 505.9	2000–5000
Mixed liquor volatile suspended solids (MLVSS) (mg/L)	3989 ± 412.2	-
Food/Mass of microorganisms (F/M) (Kg BOD_5/Kg MLSS)	0.083	0.04–0.1
Volumetric loading rate (V_L) (Kg BOD_5/m^3.d)	0.387	0.1–0.3
Return activated sludge (RAS) flow (m^3/d)	7000	-
Return activated sludge (RAS) ratio (%)	50	-
Underflow concentration (TSS in RAS) (g/L)	10.05 ± 1.45	-
Wasted activated sludge (WAS) flow (m^3/d)	120	-

Note: * Design criteria for the oxidation ditch system adapted from Metcalf and Eddy (2007).

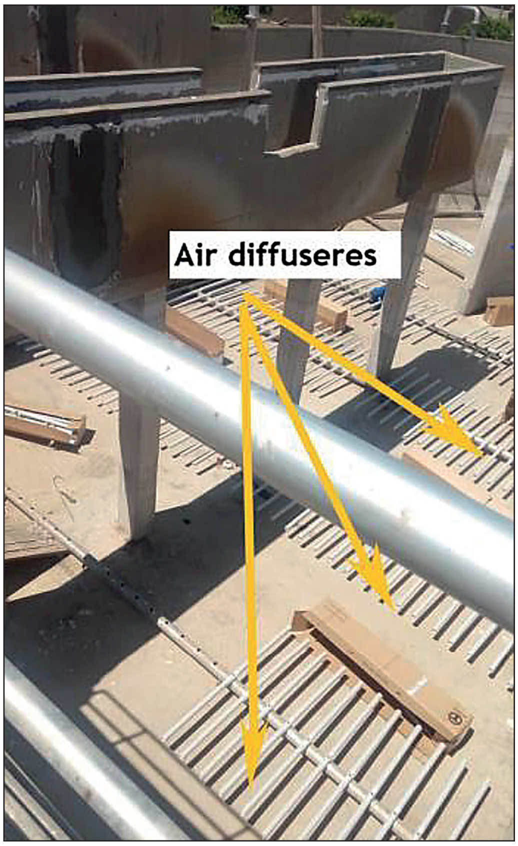

Figure 3. The air diffusers installed in the oxidation ditches

The upgraded OD has a volume of 7956 m^3 (68×26×4.5 m) and has 1088 air diffusers installed in the aerobic zone, while two mixers of 15 kWh were installed in the anoxic zone to keep the activated sludge from settling in addition to maintain a certain level of DO in it. The upgraded OD has an average mixed liquor suspended solids (MLSS) of 4352 mg/L. The ODs run under a retention time of 13.64 hours and a sludge age of 28.7 days.

Table 4 lists the operating sequence in one cycle of aerobic and anoxic conditions in the upgraded OD.

RESULTS AND DISCUSSION

Dissolved oxygen levels along the upgraded OD

Figure 5 illustrates the DO profile along the upgraded OD. DO values in general were controlled after being upgraded in a way that increases the efficiency of the biological treatment as well as controlling sludge settleability to permanently get rid of the sludge accumulation at the bottom of the ODs. In this way, it is observed that the DO values rise in the aerobic zone, while they decrease in the anoxic zone in the upgraded OD. The DO values in the aerobic zone in the upgraded OD varied from 3.8 to 4.5 mg/L, whereas in the anoxic zone they ranged from 2.0 to 3.8 mg/L. On the other hand, the mean DO value along the OD was 2.5 mg/L before upgrading. This means that the nitrification and denitrification processes can be achieved by dividing the upgraded OD into the aerobic zone and the anoxic zone in addition to controlling the DO level. These results are somewhat consistent with Metcalf and Eddy (2007), and Hartley (2008).

Effect of upgrading OD on nitrogen removal performance and sludge settleability

The removal efficiency of TN containing NH_4^+-N is shown in Figure 6. The influent TN concentrations varied from 29.7 to 47.5 mg/L, and the effluent NH_4^+-N and NO_3^--N were consistently

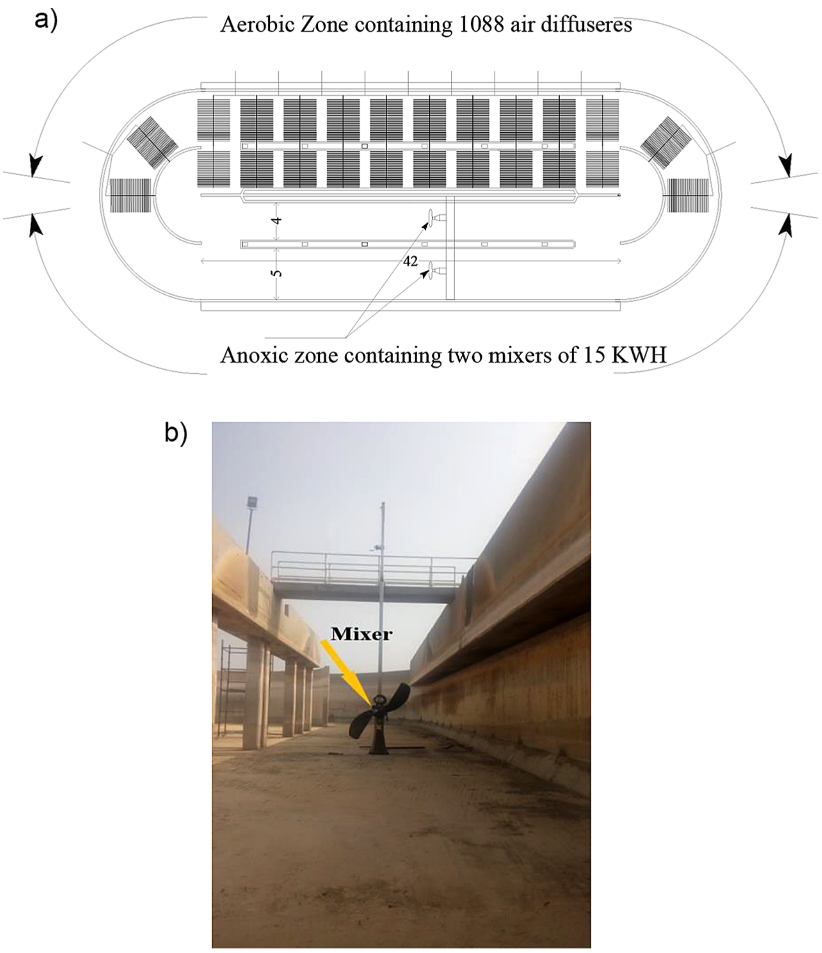

Figure 4. Upgraded oxidation ditch in Tazmant WWTP shown in (a) horizontal projection, (b) anoxic zone

Table 4. The operating sequence of the upgraded OD

Mode No.	Operating mode	Process	Time (hr.)
1	Aeration ON/ Mixer OFF	Nitrification (produce NO_3^--N)	2
2	Aeration OFF/ Mixer ON	Denitrification (reduce NO_3^--N)	2

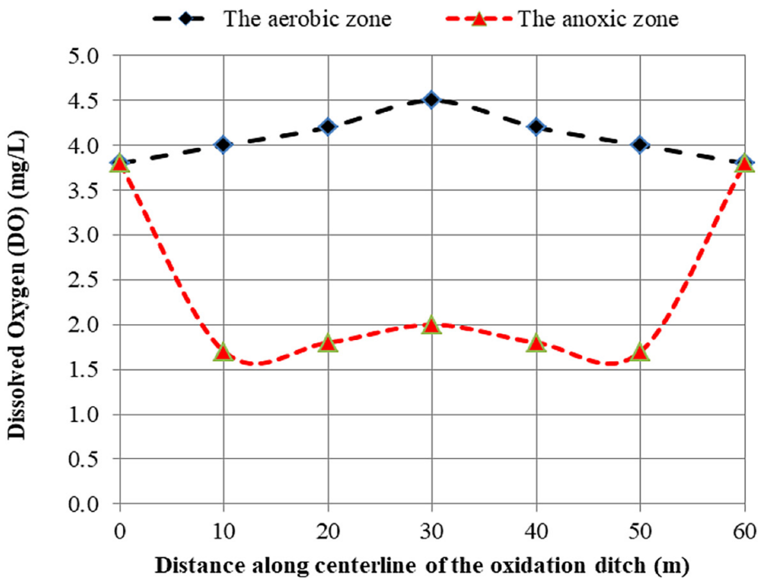

Figure 5. Dissolved oxygen profile along the upgraded OD

less than 10 mg/L. This is due to the stability of the activated sludge system during the run time of 360 days because the upgraded OD had a completely mixed water flow minimizing the impact of shock load. Figure 6 illustrates that the average TN removal efficiency was 60% assuming that TN is about equal to the sum of NH_4^+-N and NO_3^--N (Ammary and Radaideh, 2005), which could be obtained due to a highly efficient SND approach. As a result, the upgraded OD successfully removes NH_4^+-N and NO_3^--N by SND. These results are somewhat consistent with Ammary and Radaideh (2005), and Yongzhen et al. (2008).

Sludge settleability was monitored using the sludge volume index (SVI) test (Standard Methods, 2017). It is noted from Figure 7a that the better NH_4^+-N and NO_3^--N removal efficiencies correspond to the lower SVI, which reflects the efficiency of the upgraded OD in preventing the accumulation of sludge at the bottom. Effluent NH_4^+-N and NO_3^--N concentrations corresponding to a minimum SVI of 41.9 mL/g were 8.6 mg/L for NH_4^+-N and 8.6 mg/L for NO_3^--N, respectively. In the same context, it is noticed from Figure 7b that the lowest SVI corresponds to the ratio of NH_4^+-N: NO_3^--N equal to 1.0 because this ratio is optimum to remove TN and convert it to the largest amount of nitrogen gas, and then the sludge settleability becomes at its lowest value of SVI which was confirmed during the pilot runtime, as the bottom of the upgraded OD was clean and there was no trace of sludge accumulation in it. In the same context, it is also noted that the SVI values increase as the ratio of NH_4^+-N: NO_3^--N decreases or exceeds 1.0. These results are somewhat consistent with Ammary and Radaideh (2005), and Hartley (2008).

Effect of upgrading oxidation ditch on removing BOD_5, COD, and TSS

The removal efficiency of BOD_5 is shown in Figure 8. The influent BOD_5 concentrations varied from 149 to 283 mg/L, and the effluent BOD_5 was consistently less than 30 mg/L. This is due to the stability of the activated sludge system during the run time of 360 days because the upgraded OD had a completely mixed water flow minimizing the impact of shock load. Figure 8 illustrates that the BOD_5 removal efficiency varied from 89.2% to 96.5%. As a result, the upgraded OD successfully removes BOD_5 below the permissible limit for final effluent of 60 mg/L according to Metcalf and Eddy (2007). These results are somewhat consistent with Ammary and Radaideh (2005).

The removal efficiency of COD is shown in Figure 9. The influent COD concentrations varied from 361 to 512 mg/L, and the effluent COD was consistently less than 65 mg/L. This is due to the stability of the activated sludge system during the run time of 360 days because the upgraded OD had a completely mixed water flow minimizing

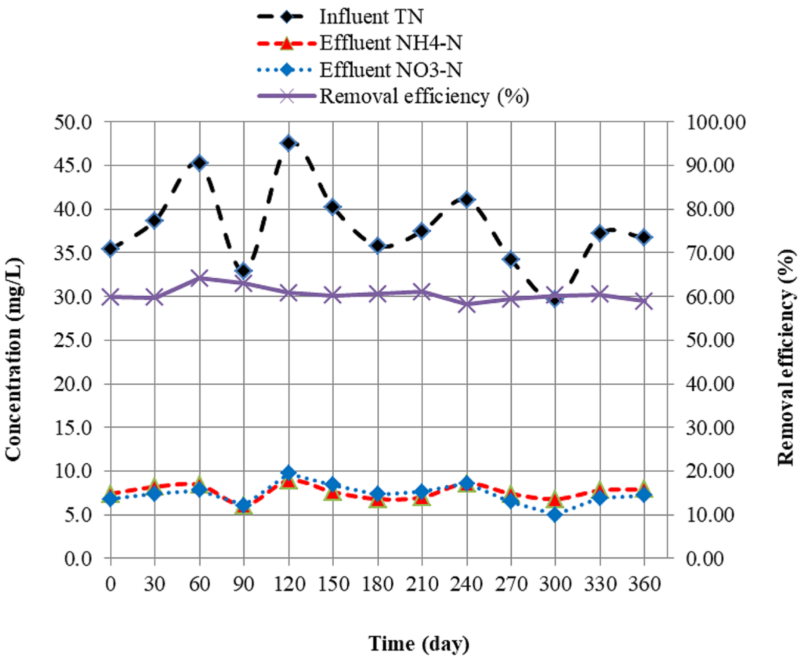

Figure 6. Nitrogen removal performance in the upgraded OD

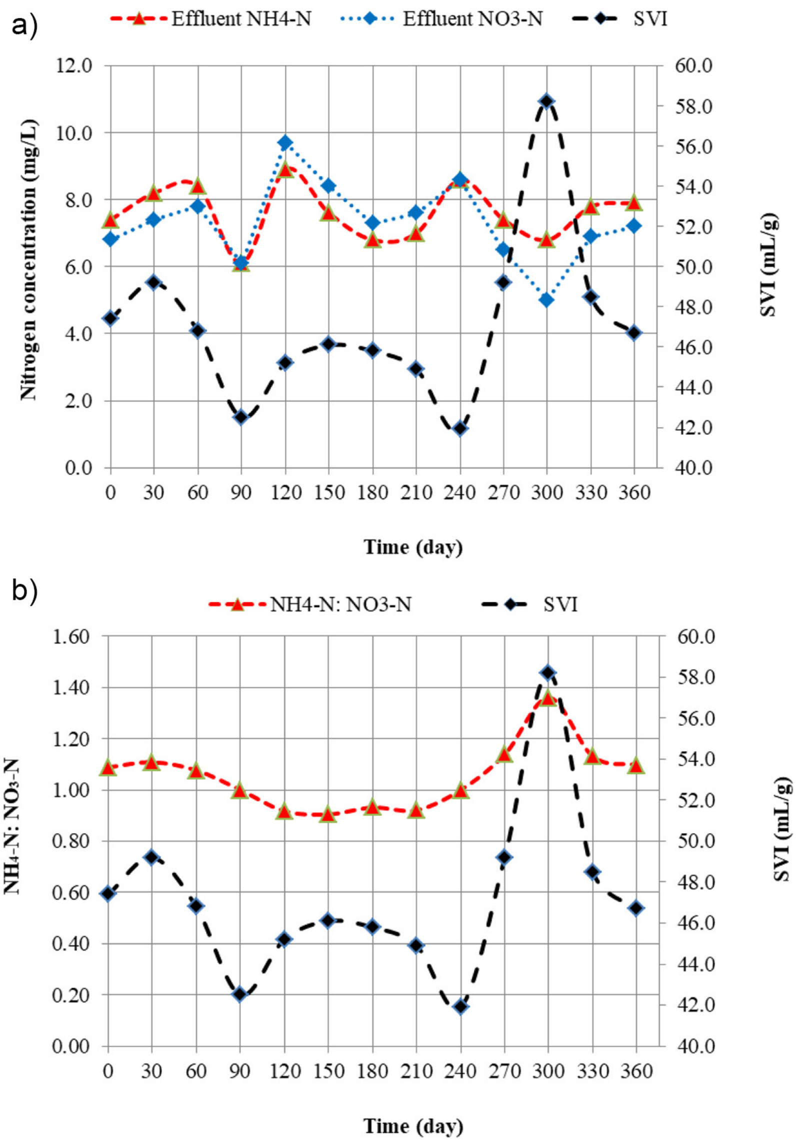

Figure 7. SVI versus (a) the effluent NH_4^+-N and NO_3^--N concentrations, (b) the NH_4^+-N: NO_3^--N ratio

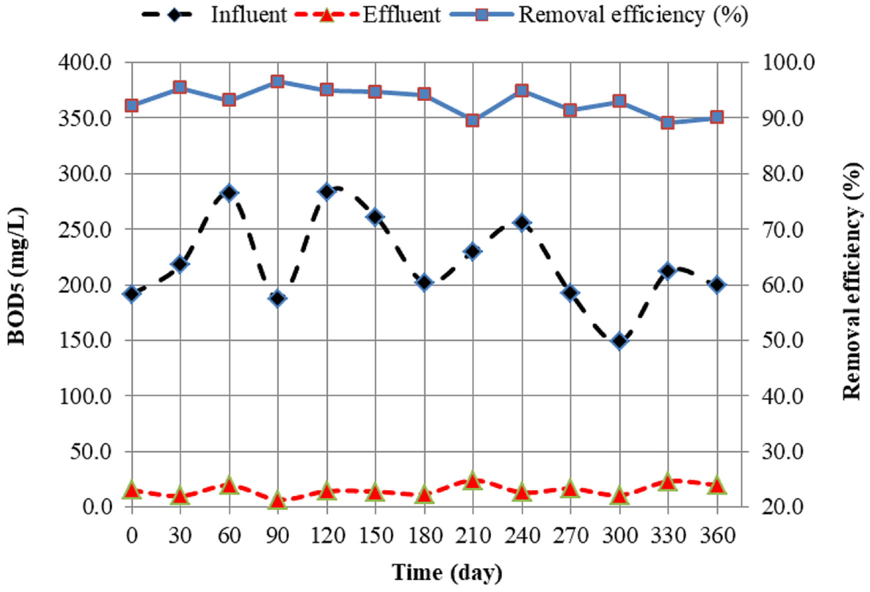

Figure 8. BOD_5 removal performance in the upgraded OD

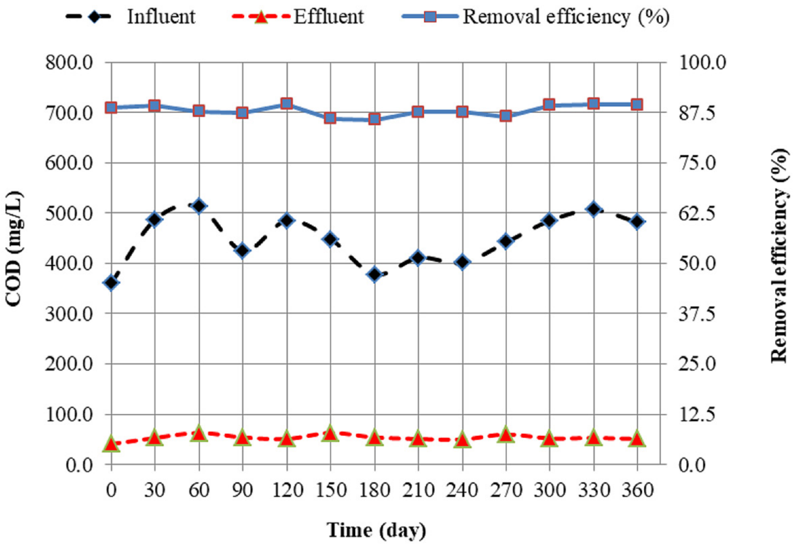

Figure 9. COD removal performance in the upgraded OD

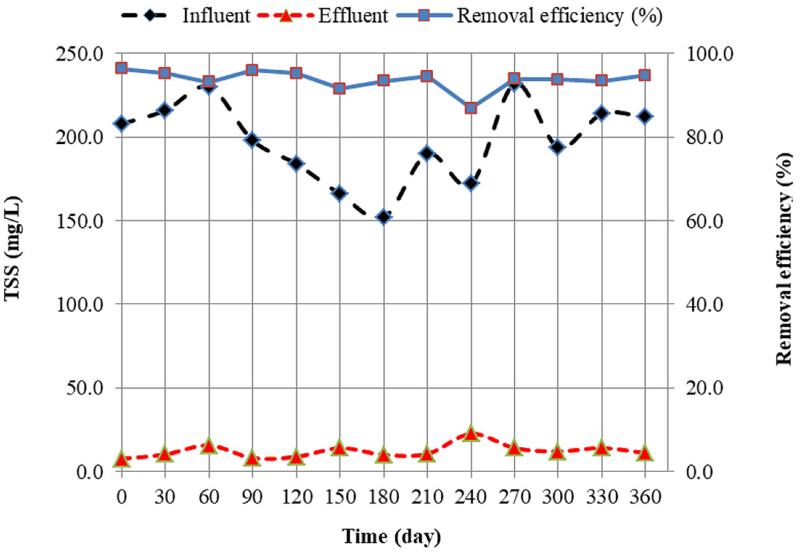

Figure 10. TSS removal performance in the upgraded OD

the impact of shock load. Figure 9 illustrates that the COD removal efficiency varied from 85.7% to 89.5%. As a result, the upgraded OD successfully removes COD below the permissible limit for final effluent of 80 mg/L according to Metcalf and Eddy (2007). These results are somewhat consistent with Ammary and Radaideh (2005), and Yongzhen et al. (2008).

The removal efficiency of TSS is shown in Figure 10. The influent TSS concentrations varied from 152 to 232 mg/L, and the effluent TSS was consistently less than 25 mg/L. This is due to the stability of the activated sludge system during the run time of 360 days because the upgraded OD had a completely mixed water flow minimizing the impact of shock load. Figure 10 illustrates that the TSS removal efficiency varied from 86.9% to 96.3%. As a result, the upgraded OD successfully removes TSS below the permissible limit for final effluent of 50 mg/L according to Metcalf and Eddy (2007). These results are somewhat consistent with Ammary and Radaideh (2005), and Yongzhen et al. (2008).

CONCLUSIONS

The present study intends to investigate the performance of the upgraded oxidation ditch system in Tazmant WWTP, Egypt by dividing the operating volume of the upgraded OD into aerobic and anoxic zones to achieve alternating aerobic and anoxic conditions in order to get the best removal of TN and eliminate the accumulation of sludge inside bottom of the upgraded OD. A number of noteworthy conclusions were drawn as follows. The influent TN concentrations varied from 29.7 to 47.5 mg/L, and the effluent NH_4^+-N and NO_3^--N were consistently less than 10 mg/L. This is due to the stability of the activated sludge system during the run time of 360 days because the upgraded OD had a completely mixed water flow minimizing the impact of shock load. The average TN removal efficiency was 60%, which could be obtained due to a highly efficient SND approach. As a result, the upgraded OD successfully removes NH_4^+-N and NO_3^--N by SND. The better NH_4^+-N and NO_3^--N removal efficiencies correspond to the lower SVI, which reflects the efficiency of the upgraded OD in preventing the accumulation of sludge at the bottom. Effluent NH_4^+-N and NO_3^--N concentrations corresponding to a minimum SVI of 41.9 mL/g were 8.6 mg/L for NH_4^+-N and 8.6 mg/L for NO_3^--N, respectively. The lowest SVI corresponds to the ratio of NH_4^+-N: NO_3^--N equal to 1.0 because this ratio is optimum to remove TN and convert it to the largest amount of nitrogen gas, and then the sludge settleability becomes at its lowest value of SVI which was confirmed during the pilot runtime, as the bottom of the upgraded OD was clean and there was no trace of sludge accumulation in it. The upgraded OD successfully removes BOD_5, COD, and TSS below the permissible limit for final effluent of 60, 80, and 50 mg/L respectively.

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