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A New Approach for Upgrading of Sewage Treatment Plants to Accommodate Excess Organic and Hydraulic Loads

Ibrahim Gar Al-Alm Rashed[1], Ahmed El-Morsy[2], Mohamed Ayoub[2*]

[1] Faculty of Engineering, Mansoura University, Mansoura 35516; Higher Institute for Engineering and Technology, New Damietta, Egypt

[2]Public Works Engineering Department, Faculty of Engineering, Tanta University, Tanta, 31511, Egypt

ABSTRACT

The communities with high population density suffer from limited land availability for construction of new sewage treatment plants or expansion of the existing plants, which suffer from receiving of excess hydraulic and/or organic loads. The undertaken work is devoted to investigate the feasibility of upgrading these plants using chemically enhanced primary treatment (CEPT) with hydraulic clari-flocculation. CEPT produces large amounts of primary sludge, which can be digested anaerobically to produce biogas. The results showed that a homogenous mixture of 67% alum and 33% sea-salt by weight can be used with dose of 40 mg/L as a suitable coagulant in addition to a range between 60-90 m/d of surface overflow rate as the optimum conditions for CEPT of sewage. These conditions result in removal efficiencies in the range between 52-70% of BOD_5, 54-68% of COD and 76-88% of TSS. These results enable the primary sedimentation tank (PST) to accommodate double of its design capacity with very simple modifications in the raw sewage inlet to be chemically enhanced primary sedimentation tank (CEPST) according to the present study. In addition, CEPT maintains the operational conditions of activated sludge system in the recommended limits. Finally, CEPT for upgrading the present WWTP is definitely advantageous in reducing the capital costs by 30% and the treatment costs by 28%.

Keywords: Chemically enhanced primary treatment; hydraulic loads; organic loads; upgrading; wastewater treatment

1. INTRODUCTION

Egyptian communities with high population density suffer from shortage and limited land availability for construction of new sewage treatment plants or expansion of the existing plants, which suffer from receiving of excess hydraulic and/or organic loads. Therefore, this problem creates research challenge for upgrading of the existing sewage treatment plants on the same occupied area, or with very limited expansions in land requirements. Consequently, the proper upgrading concept is to apply chemical enhanced primary treatment (CEPT) technology.

CEPT is a wastewater treatment method that serves as an attractive alternative to the conventional primary treatment. It can also be used as an efficient preliminary step of the biological secondary treatment processes. CEPT adopts coagulation and flocculation, and it accomplishes remarkable increases in the removal of common pollutants from the influent (Ødegaard, 1989; Rashed et al., 1997). Chemical precipitation is the technique of the CEPT

Corresponding to: eng.ayob@yahoo.com

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process, the main idea of chemical precipitation that it converts dissolved substances to insoluble particles, which can be flocculated and separated from the liquid. Removal efficiencies depend on coagulant (type-dosage), mixing times, and the care with which the processes are monitored and controlled. With chemical precipitation, it is possible to remove about 80-90% of total suspended solids (TSS), 50-80% of biochemical oxygen demand (BOD_5), 30-70% of chemical oxygen demand (COD), 80-95% of the phosphorus as well as 20-25% of the nitrogen in the primary sedimentation. In comparison, well designed and operated primary settling tanks without addition of chemicals may remove between 50-70% of total suspended solids (TSS), 25-40% of biochemical oxygen demand (BOD_5) and 5-10% of phosphorus (Metcalf and Eddy, 2003; Mahvi et al., 2005; O'Melia, 1970; Ødegaard, 1989; Rashed et al., 1997; Sarparastzadeh et al., 2007).

Rashed et al. (2013a) applied the analytic hierarchy process (AHP) for evaluation of different alternatives of coagulants (types-doses) according to four main criteria (i.e. removal efficiencies, sludge volume, coagulant cost, and pH variation). In addition, the removal efficiencies were divided into five sub-criteria, including COD, BOD_5, TSS, T-P, and T-N removals. Rashed et al. (2013a) demonstrated the feasibility of using homogenous mixtures of alum and sea salt, which resulted in satisfied values of pollutants removal, reaching up to 85% of COD, 90% of BOD_5, 94% of TSS, 92% of T-P, and 20% of T-N. Moreover, the least pH variation was recorded with the application of these mixtures; these results were obtained using jar test apparatus with 15 minutes of flocculation followed by 30 minutes of sedimentation rather than 2 hours in the conventional primary sedimentation. This requires redesign and restructuring of the conventional primary sedimentation tanks to double their design discharges (Engelhardt, 2010; Rashed et al., 2013b).

The quantity of sludge produced from the conventional wastewater treatment plants is approximately 1% of the quantity of treated wastewater while, the key problems of CEPT of wastewater are the costs of chemicals and the production of excessive sludge volumes. Moreover, CEPT of wastewater produces about 1.5-2.0 fold more sludge than that produced by conventional primary treatment (Huang and Li, 2000; Semerjian and Ayoub, 2003; Turovskiy and Mathi, 2006; Xu et al., 2005).

In the present study, Nawag wastewater treatment plant (WWTP) was selected as a practical example for the proposed upgrading of wastewater treatment plants using CEPT. This plant receives wastewater from Nawag village which located in El-Gharbia Governorate (about 100 km north Cairo, Egypt). Nawag WWTP was designed to treat 3000 m^3/d of settled wastewater which undergone primary treatment within the septic tanks connected with a collection network of small bore sewer system (Abd El- Aziz, 2010; Fadel et al., 2005). Recently, the plant suffers from poor performance in the treatment process, as well as it receives excess flow rate reaches to about 3600 m^3/d; this problem emerges in conjunction with the rapid population increase and urbanization in Nawag village. The random urban extensions of Nawag village dispose wastewater directly in the collection network without septic tanks, which causes excess flow rate and negatively change the characteristics of influent sewage to Nawag WWTP. The biological treatment has been processed using activated sludge, which is operated in the aeration tank followed by final sedimentation tanks as shown in Figure 1.

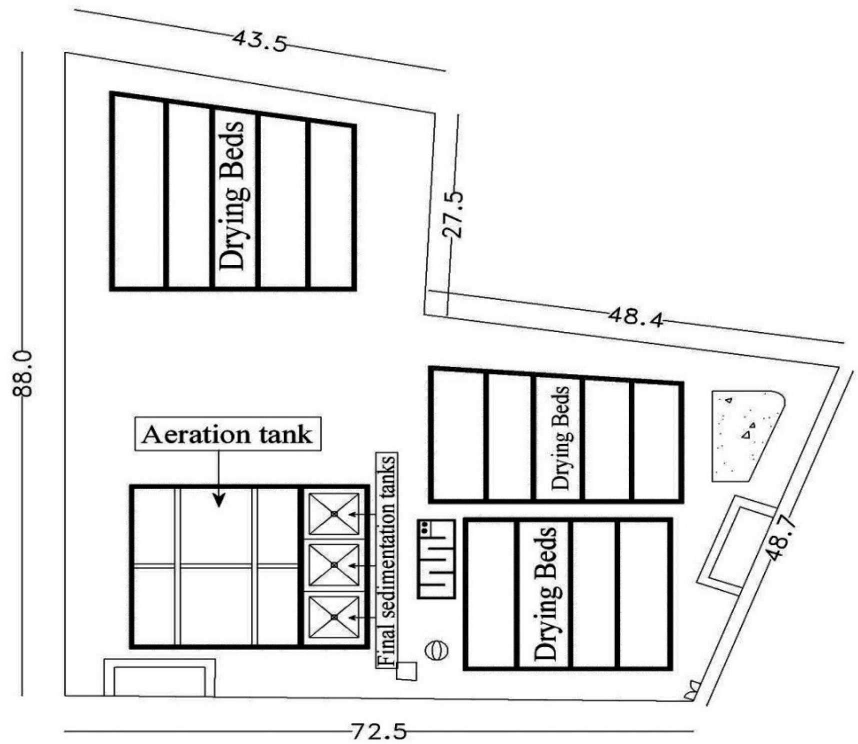


Figure 1 A schematic diagram of Nawag wastewater treatment plant in the current status

Table 1 Wastewater characteristics in Nawag WWTP

Parameter	Current status				Design values for aeration tank	
	Raw sewage		Final effluent		Influent sewage*	Final effluent
	Range	Average	Range	Average		
pH	7.3-7.9	7.6	6.9-8.1	7.5	-	-
TSS, mg/L	280-400	340	28-52	40	150	30
COD, mg/L	620-900	760	70-110	90	300	50
BOD_5, mg/L	260-420	340	34-96	65	140	20
T-P, mg/L	8.9-10.6	9.8	-	-	-	≤4
T-N, mg/L	22-26	24	-	-	-	≤18
$N\text{-}NH_3$, mg/L	14-18	16	-	-	-	≤5

*Influent sewage is primary settled sewage in septic tanks then collected in sewerage network to Nawag WWTP

The undertaken work was devoted to investigate the feasibility of upgrading wastewater treatment plants using CEPT, and to evaluate this upgrading technically and economically.

2. MATERIALS AND METHODS

2.1 Wastewater characteristics

Recently, wastewater characteristics in Nawag WWTP have been completely changed due to direct disposal of sewage in the sewerage network without primary settling (in septic tanks). Table 1 represents wastewater characteristics in Nawag WWTP in the current status, as well as it displays the design values of wastewater characteristics (influent settled wastewater in septic tanks). The analyses of raw and treated wastewater samples were conducted and measured on the basis of Standard Methods (1998). Total solids (TS) was conducted and measured using drying oven BINDER® company, and the analytical balance OHAUS®, Germany. These apparatuses were used also with paper filter for conducting of total suspended solids (TSS). Volatile solids (VS) were conducted and measured using muffle furnace WISE Therm® (EHP-14), Korea, and the analytical balance OHAUS®, Germany. The 5-days biochemical oxygen demand (BOD_5) was measured using BOD Incubation Fisher Scientific®, USA while, the chemical oxygen demand (COD) was conducted using COD reactor DINKO®, and Spectrophotometer *biochrom*®, Model Libra S12. This spectrophotometer was also utilized in the measuring of the total phosphorus (T-P), and the total nitrogen (T-N).

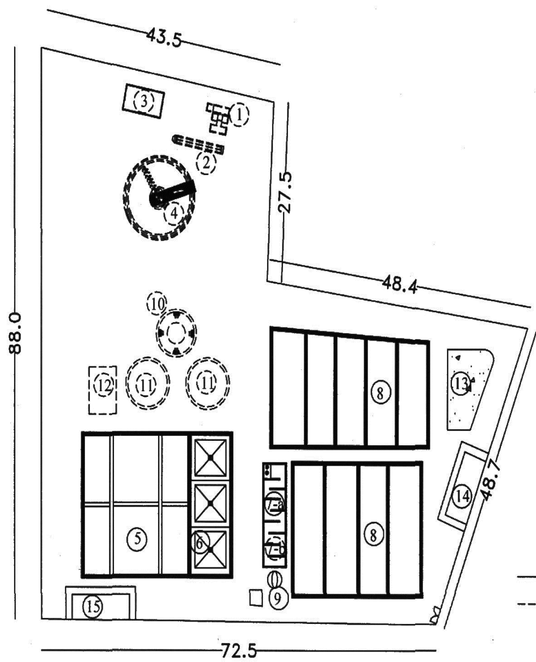
2.2 Coagulant

In the present study, sea salt (CAS number 7647-14-15), and alum [$Al_2(SO_4)_3 \cdot 18H_2O$, CAS number* 10043-01-3] were used to form a homogenous mixture of alum and sea salt (67% alum+33% sea-salt by weight). This mixture was the most suitable coagulant for direct precipitation of raw sewage according to Analytic Hierarchy Process (AHP) (Rashed et al., 2013a). Direct precipitation of de-gritted raw sewage with characteristics similar to wastewater characteristics of Nawag WWTP, using the previously mentioned mixture with a dose of 40 mg/L ranked the first position in AHP analysis (Rashed et al., 2013a). Therefore, 40 mg/L of homogenous mixture of (67% alum + 33% sea-salt by weight) was applied as a coagulant; stock solution of coagulant with concentration of 10 mg/L was produced by mixing the coagulant with distilled water, and then adjusting the coagulant dose using dosing pump.

2.3 The proposed upgrading

Upgrading of Nawag WWTP aims to increase its design capacity from 3000 m^3/d to 6000 m^3/d, as well as to reduce the excess influent organic load by chemical pre-precipitation on the same occupied area as shown in Figure 2-a. Consecutive units of deceleration chamber, including screens to remove large objects carried in the sewage stream, and grit removal chamber to settle sand and grit, should be constructed in the proposed upgrading. The chemical pre-precipitation can be used to make wastewater characteristics suitable for the following designed activated sludge system via constructing a new chemically enhanced primary sedimentation tank (CEPST) as shown in Figure 3-b. CEPST is a swirl flow hydraulic clari-flocculator investigated by Rashed et al. (2013b) to carry double design capacity of a conventional primary sedimentation tank with the same dimensions by applying one hour (20 minutes flocculation + 40 minutes sedimentation) as a retention time for CEPST instead of 2 hours for primary sedimentation tank (PST) as shown in Figure 3-a. On the other hand, CEPT produces large amounts of primary sludge with greatly organic content, which can be treated anaerobically to produce biogas; a primary sludge thickener and anaerobic sludge digester should be constructed to complete the process of biogas production as shown in Figure 2-b.

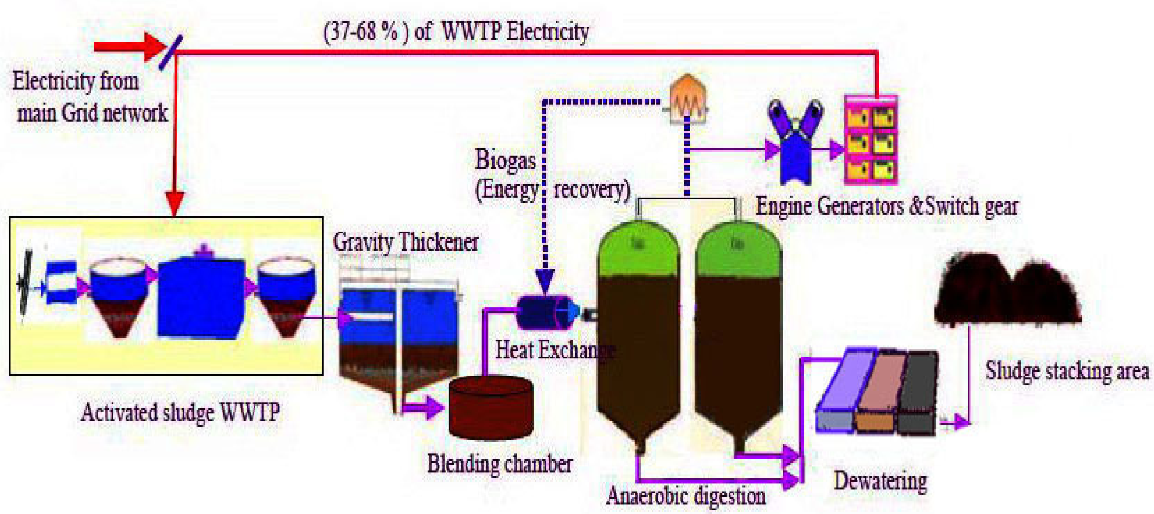
CEPST is the core of upgrading WWTP using chemical pre-precipitation. Modeling of PST and CEPST were demonstrated as distorted models on the basis of Froude Number (Young et al., 2007); the experimental model was designed to simulate PST and CEPST as shown in Figures 3-a, and 3-b. CEPT was completed by integrating three sequential processes (i.e. coagulation by inline mixing of coagulant with de-gritted raw sewage via a centrifugal feed pump as shown in Figure 4-c, flocculation by swirling flow from the tangential inlet to end of the flocculation zone, and sedimentation, which starts after flocculation to position of outlet weirs). Thereafter, the primary settled wastewater would be ready to be treated biologically through aeration tanks. Figure 4 shows the contents of the experimental model.



No.	Description	Remarks
1	Deceleration chamber and screens	
2	Grit removal chamber	
3	Chemicals and pumping building	
4	Chemically enhanced primary sedimentation tank CEPST	
5	Aeration tanks	
6	Final sedimentation tanks	
7	Chlorination basin	(a) Currently working (b) Extensions
8	Drying beds	
9	Filtered water pump station	
10	Sludge thickener	Sludge treatment facilities
11	Anaerobic sludge digester	
12	Electricity generator using biogas	
13	Sludge storage zone	
14	Transformer and generator building	
15	Adminstrative building	

——— The existing units
- - - - - The proposed units for upgrading

(a)



(b)

Figure 2 The proposed upgrading for Nawag wastewater treatment plant (a) General layout, (b) Flow diagram of the sludge treatment scenario by using anaerobic digestion technology (Ghazy et al., 2009)

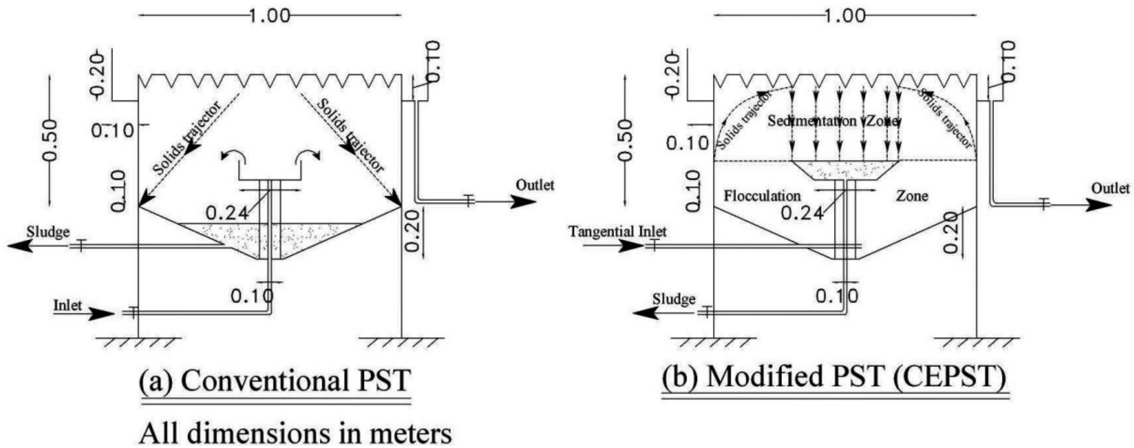


Figure 3 Experimental model of (a) Conventional primary sedimentation tank (PST), (b) Chemically enhanced primary sedimentation tank (CEPST)

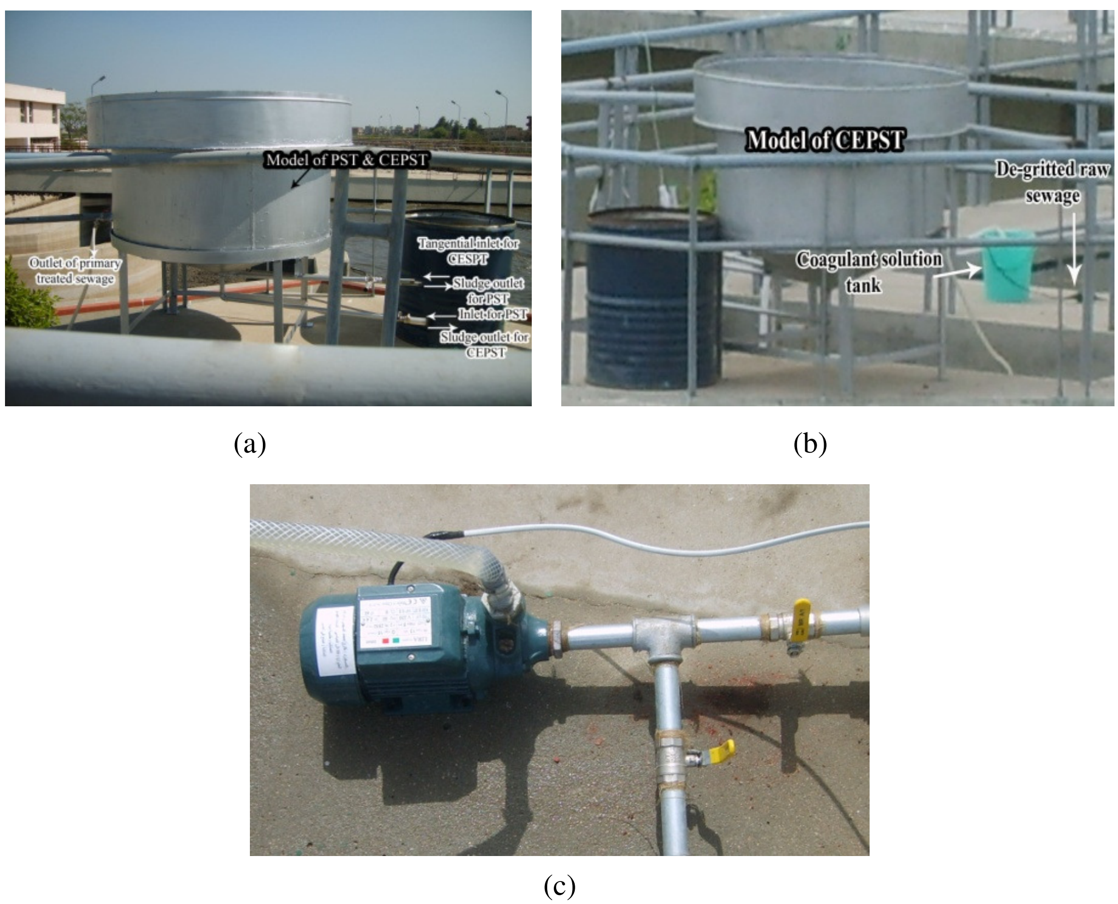


Figure 4 (a) Different arrangement of inlet and outlet pipes in the experimental model of PST and CEPST, (b) The experimental model for CEPT of sewage, (c) Inline mixing of coagulant with de-gritted raw wastewater

The modeled operational conditions for the experimental models of PST and CEPST were the surface loading rate ranged between (30-90) m3/m2/d whereas, the corresponding total retention time ranged between (120-40) minutes. The total retention time of CEPST was the sum of retention time of the flocculation process, which takes 33% of the total retention time, in addition to retention time of the sedimentation process, which takes 67% of the total retention time of CEPST. Moreover, the retention time of the flash (inline) mixing was in the range between (10-30) seconds.

3. RESULTS AND DISCUSSION

3.1 Effect of surface overflow rate

The variations of removal efficiencies of TSS, BOD_5, COD, T-P, and T-N are shown in Figure 5. It is noticed that removal efficiencies of BOD_5, and COD using CEPT technology via CEPST model were greater than double their values resulted from model of the conventional primary sedimentation (PST model). Therefore, CEPST may be able to carry double the design discharge of PST and precipitate the excess organic loads. Metcalf and Eddy (2003) recommended a range of surface overflow rate between 30-50 m/d for PST to remove about 60% of TSS and 30% of BOD_5. While, a range between 60-90 m/d of surface overflow rate has been considered to be the optimum range for CEPST to remove about 78% of TSS, 60% of BOD_5, 60% of COD, 76% of T-P, and 12% of T-N. Thus, the use of CEPT facilitates to diminish the organic loading to the consecutive biological treatment by forwarding the excess organic load to the primary sedimentation then to the anaerobic sludge digestion.

3.2 The proposed scenario for sludge treatment using anaerobic digestion

The mixed sewage sludge (primary and secondary sludge) should be pumped to thickening facilities (a gravity thickener with a volume of 38 m^3). After the gravity thickening, the thickened sludge can be pumped to the anaerobic digesters (two digesters with a volume of 379 m^3/ digester) for a retention time of 20 days. The estimated biogas production (with about 65% of methane) from sewage sludge generally ranges from 0.8-1.1 m^3/Kg of volatile solids destroyed (Turovskiy and Mathi, 2006). On the other hand, Ghazy et al. (2009) reported that the large portion of produced biogas may be used for the operation of hot water boilers, which are operated to heat the raw sewage sludge in the anaerobic digesters. In addition, the excess digested gas can be used to generate electricity representing about 37-68% of the power consumed in the WWTP as shown in Figure 2-b. Table 2 shows characteristics of the different types of the primary sludge in the present study as compared to the previous literature (Fytili and Zabaniotou, 2008; Turovskiy and Mathi, 2006). From Table 2, it is noticed that the primary sludge after CEPT has a higher organic content than the primary sludge after the conventional primary treatment. This leads to relatively increasing in productivity of the biogas after CEPT, consequently, less drying beds are required for sludge treatment.

3.3 Effect of CEPT on the operational conditions of Nawag WWTP

The optimum surface overflow rate of CEPST was considered to be 60 m/d with regard to both removal efficiencies of pollutants and accommodation the excess hydraulic load (i.e. 6000 m^3/d instead of 3600 m^3/d) as previously mentioned. Table 3 represents a summary of the operational conditions of Nawag WWTP from the current status, as well as from the proposed upgrading. Moreover, the results were compared with the typical design criteria for the conventional activated sludge process

(Metcalf and Eddy, 2003).

In Table 3, it is noticed that the operational conditions in the case of the proposed upgrading are still in the appropriate values compared with the current status. Moreover, the problem of increasing the volumetric loading rate in the current status (i.e. 1.02 Kg $BOD_5/m^3 \cdot d$) can be solved using the proposed upgrading, which can significantly reduce the volumetric loading rate to be 0.64 Kg $BOD_5/m^3 \cdot d$, and to make it in the typical design limits (i.e. 0.3-0.7 Kg $BOD_5/m^3 \cdot d$). On the other hand, the excess sludge production can be treated using anaerobic digesters to produce about 720 m^3/d of biogas, which can be used to generate about 940 Kwh/d of electric power.

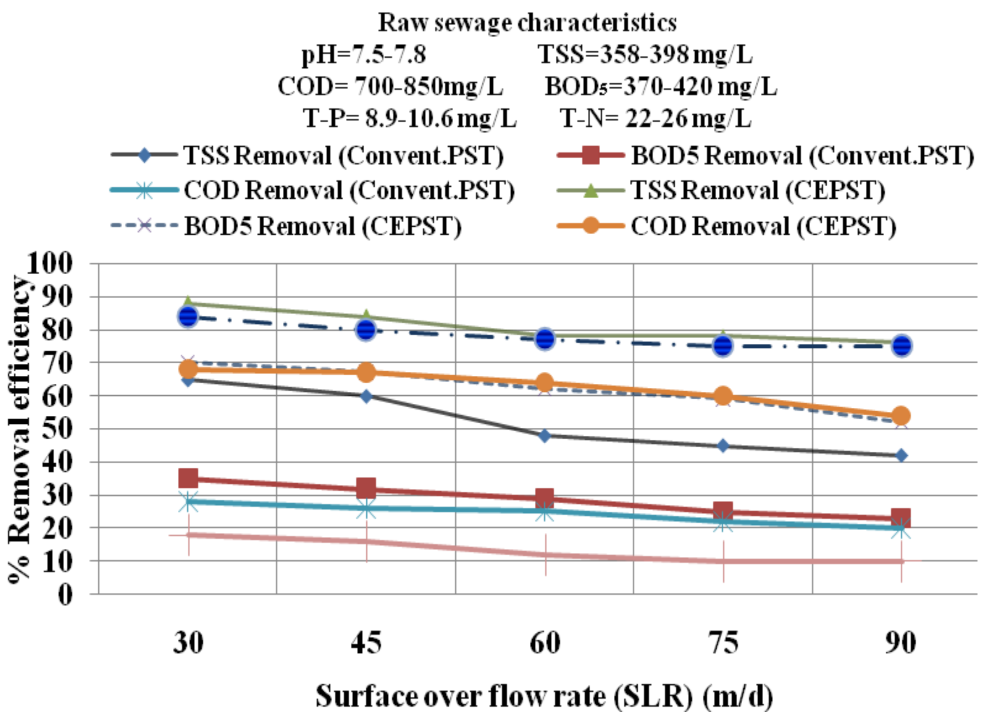


Figure 5 Relationship between surface overflow rate and pollutants removal in the primary sedimentation

Table 2 Characteristics of the primary sludge in the present study as compared to the previous literature (Fytili and Zabaniotou, 2008; Turovskiy and Mathi, 2006)

Parameter	After the conventional primary treatment (after PST)	After the CEPT (after CEPST)	After the conventional primary treatment (Pervious literature)
Total solids (TS), g/L	22.9	30.8	20-80
Volatile solids (VS), g/L	19.5	28.3	13-52
Volatile solids of bio-solids (VS), g/L	6.8	7	24-48

Table 3 Operational conditions for Nawag WWTP

Parameter	The current status	The proposed upgrading	Design criteria (Metcalf & Eddy, 2003)
Average influent flow rate (m^3/d)	3600	6000	-
Volume of primary sedimentation tank (m^3)	-	250	-
Volume of aeration tank (m^3)	1200	1200	-
Volume of final sedimentation tank (m^3)	400	400	-
Aeration period (θ) (hr)	8	5	4-8
Mean cell residence time (θ_c) (day)	10	10	3-15
Mixed liquor suspended solids (MLSS) (mg/L)	2750	1500	1000-3000
Food/Mass of microorganisms (F/M) (Kg BOD_5/Kg MLSS)	0.3	0.3	0.2-0.4
Volumetric loading rate (V_L) (Kg BOD_5/m^3.d)	1.02	0.64	0.3-0.7
Waste sludge flow rate (Q_w) (m^3/d)	35	35	-
Mass of solids produced (Kg/d)	960	1898	-
Volume of anaerobic digester (m^3)	-	758	-
Total solids pumped to drying beds (Kg/d)	960	1178	-
Biogas production (m^3/d)	-	720	-
Electric power production rate from biogas* (Kwh/d)	-	940	-

*Electricity production rate can be estimated as 800 Kwh/total solids (t/d), or 1.3-1.5 Kwh/m^3 of biogas as reported in US.EPA, (2008).

Table 4 Results of the comparative cost analysis for Nawag WWTP

Item		The current status (3600 m^3/d)	The proposed upgrading (6000 m^3/d)
The fixed capital costs (EGP/m^3/d)	Civil works (EGP/m^3/d)	1500	1050
	Mechanical and Electrical works (EGP/m^3/d)	1000	700
The operating costs (EGP/m^3)	Chemical costs (EGP/m^3)	Can be neglected	0.043
	Power costs (EGP/m^3)	0.214	0.100
	Maintenance (EGP/m^3)	0.083	0.058
	Labor requirements (EGP/m^3)	0.094	0.088
	Depreciation (EGP/m^3)	0.288	0.200
Total treatment cost of 1 m^3 of wastewater(EGP)		0.679 ≈ 0.68	0.489 ≈ 0.49

3.4 The comparative cost analysis

The comparative cost analysis was conducted for the current status versus the proposed upgrading of Nawag WWTP on the basis of the fixed capital costs as well as the operating costs which include costs of chemicals, power, labor requirements, and depreciation of the fixed capital costs (i.e. civil works, and electro-mechanical works) as presented in Table 4.

The obtained results revealed that using of CEPT technology for upgrading of Nawag WWTP is definitely advantageous in reducing of the capital costs by 30% and the treatment costs by 28%.

CONCLUSIONS

The feasibility of upgrading WWTPs using chemical enhanced primary treatment has been investigated. The obtained results reveal that:

With chemical enhanced primary treatment, it can be achieved double the removal efficiencies of BOD_5, and COD comparing with the conventional primary sedimentation.

The optimum surface overflow rate ranges between 60-90 m/d for chemically enhanced primary sedimentation versus 30-50 m/d for the conventional primary sedimentation. This enables the chemically enhanced primary treatment to accommodate excess hydraulic loads may reach to twice its value with the conventional primary sedimentation.

Homogenous mixture of 67% alum and 33% sea-salt by weight can be used as a suitable coagulant for chemically enhanced primary treatment of sewage which resulted removal efficiencies reach to about 78% of TSS, 60% of BOD_5, 60% of COD, 76% of T-P, and 12% of T-N.

Chemically enhanced primary treatment maintains the operational conditions in appropriate values with respect to the recommended design criteria for activated sludge system, especially the volumetric loading rate, which can be significantly reduced to about 37%.

Chemically enhanced primary treatment for upgrading WWTP is definitely advantageous in reducing of the capital costs by 30% and the treatment costs by 28%.

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