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ECONOMIC ANALYSIS: TRICKLING FILTER/ACTIVATED SLUDGE OR NITRIFYING TRICKLING FILTER/ACTIVATED SLUDGE?

ANALIZA EKONOMICZNA: ZŁOŻE ZRASZANE/OSAD CZYNNY CZY NITRYFIKACYJNE ZŁOŻE ZRASZANE/OSAD CZYNNY?

Abstract: The performance and economic simulation and modeling are crucial for accurate and rapid designing, construction, and forecasting future economic needs of municipal wastewater treatment plants (MWWTPs). In this study, combined nitrifying trickling filter/activated sludge (NTF/AS) process was suggested for the modernization of a MWWTP and the performance and economics of MWWTPs based on the combined TF/AS process and combined NTF/AS process were analyzed and compared. In real, the performance, total project construction, total operation labor, total maintenance labor, total material, total chemical, total energy, and total amortization costs of these proposed MWWTPs were calculated and compared. Under the used design criteria and operational conditions in this study, the project construction cost of the MWWTP based on TF/AS was 15.25 % higher than that of the MWWTP based on NTF/AS. Also, MWWTP based on NTF/AS was cost effective and the material and amortization costs for both plants were higher in comparison with the operation, maintenance, energy, and chemical costs. It is necessary to note that this study is a computer simulation for a case and drawing general conclusions only on the basis of this simulation may be insufficient.

Keywords: wastewater treatment plant, economic analysis, trickling filter, activated sludge

Introduction

Domestic and industrial wastewaters can contain nitrogen compounds [1-8] which total nitrogen in wastewater includes ammonia, nitrate, particulate organic nitrogen, and soluble organic nitrogen [2, 3]. Eutrophication of the rivers [9], toxic effects on aquatic life even in very low concentration [1, 10], undesired odors and several diseases [2, 11] have been listed as the environmental problems or negative impacts of ammonia and other nitrogen compounds. The maximum concentration of ammonia and ammonia compounds allowed for the fish at a temperature of 18 °C and pH of 5-7 is about 2 mg/dm^3 [1, 12]. Biological treatments [13], nitrification-denitrification processes [5, 14], ion exchange process [15], natural or synthetic adsorbents [16], and membrane processes, specially pressure driven

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process [5, 17, 18] have been reported in the literature for ammonium removal from wastewater.

In recent years, wastewater treatment plants (WWTPs) have been modeled and simulated because of the need to assess different solutions prior to their effective realization [4, 19-23]. In addition to technical, engineering and process related aspects of WWTPs, cost is an important consideration for the development and assessment of treatment alternatives, and can affect the economic feasibility of these alternatives. Thus, economic modeling and cost estimation are crucial for accurate and rapid designing, construction, and forecasting future economic needs of WWTPs [4, 24].

Biological treatment processes can be divided into suspended growth processes (e.g. activated sludge (AS) process, oxidation ditch, contact stabilization activated sludge, extended aeration activated sludge, step aeration activated sludge, pure oxygen activated sludge, aerated lagoons, etc.) and attached growth processes (e.g. trickling filter (TF), rotating biological contactor (RBC), etc.) [5, 7].

Drewnowski et al. [25] evaluated the effect of the improvement performed at a large-scale WWTP by means of modeling works, with the aim to determine the influence of the modernization over the process performance. They concluded that the energy consumption because of the aeration reduced about a 20 % maintaining the effluent quality [25].

The combined TF/AS process can be designed at high organic loads which a unique characteristic of this process is the intermediate clarifier. Generated solids in the TF are separated by the intermediate clarifier before partially treated wastewater enters the aeration tank or AS process. It is mostly a preferred mode of operation where NH_3-N removal is needed [26]. In this study, combined nitrifying trickling filter/activated sludge (NTF/AS) process was suggested for the modernization of a municipal wastewater treatment plant (MWWTP) and the performance and economics of MWWTPs based on the combined TF/AS process and combined NTF/AS process were simulated and compared. In real, the performance, total project construction, total operation labor, total maintenance labor, total material, total chemical, total energy, and total amortization costs of these proposed MWWTPs were estimated and compared.

Material and methods

Case study and influent wastewater

In order to base our study on a real case for analysis, a MWWTP in Iran was selected which is located in Tehran. The information of this plant was obtained from Mohagheghian et al. work [27]. The biological treatment of this plant is combined TF/AS process. It serves 2,100,000 people. The characteristics of influent wastewater used in this analysis have been given in Table 1. In this study, the sludge retention time (SRT), mean influent flow, mean influent chemical oxygen demand (COD), mean influent biological oxygen demand (BOD), mean influent suspended solids (SS) and average summer temperature of this plant were obtained from Mohagheghian et al. [27]. Besides, values of minimum influent flow, maximum influent flow, % volatile solids, soluble COD, soluble BOD, Total Kjeldahl Nitrogen (TKN), soluble TKN, ammonia, total phosphorus, pH, settleable solids, oil and grease, non-degradable fraction of volatile suspended solids (VSS) and average winter temperature were assumed by the author for the performance and cost estimation.

Table 1

The characteristics of influent wastewater

Parameter	Value
Mean influent flow [m^3/h]	15000
Minimum influent flow [m^3/h]	14000
Maximum influent flow [m^3/h]	16000
Influent COD [mg/dm^3]	515
Soluble COD [mg/dm^3]	300
Influent BOD [mg/dm^3]	235
Soluble BOD [mg/dm^3]	80
Influent SS [mg/dm^3]	230
Volatile solids [%]	75
Average summer temperature [°C]	25.5
Average winter temperature [°C]	5
Total Kjeldahl Nitrogen (TKN) [mgN/dm^3]	40
Soluble TKN [mgN/dm^3]	28
Ammonia [mgN/dm^3]	25
Total phosphorus [mgP/dm^3]	8
pH	7.6
Settleable solids [cm^3/dm^3]	10
Oil and grease [mg/dm^3]	100
Non-degradable fraction of VSS [%]	40

MWWTP based on combined trickling filter/activated sludge (TF/AS)

The TF is an attach growth treatment system that uses microorganisms attached to a medium (plastic or mineral inert media) to remove organic matter from wastewater [26, 28-30]. A distribution system, containment structure, rock or plastic media, underdrain, and ventilation system are typical components of a TF and the TF process usually comprises an influent pump station, TF, TF recirculation pump station, and clarifier [26]. Low-rate filters (load ranging less than 40 kg BOD_5/100 m^3·d), intermediate-rate filters (load ranging up to 64 kg BOD_5/100 m^3·d), high-rate filters (load ranging from 64 to 160 kg BOD_5/(100 m^3·d), and roughing filters (load ranging from 160 to 480 kg BOD_5/(100 m^3·d)) are four basic categories of filters based on the organic loading of the TF [29].

An aeration tank, a settling tank or clarifier, and a sludge return or recirculation line are applied in the conventional or plug flow AS process to treat wastewater. A high ratio of organic loading (i.e. food/microorganism (F/M)) to the mixed liquor at the beginning of the reactor is the major feature of a plug flow configuration. Because of the little longitudinal mixing in a plug flow tank except for that which is caused by diffused aeration, substrate can be used up and the mass of microorganisms can be enhanced due to cell reproduction by flowing liquor through its length. Much of the oxygen can be consumed by nitrification and endogenous respiration upon being sufficiently low F/M ratio in the latter stages of the reactor. The ability to handle shock loads can be decreased due to the lack of longitudinal mixing and microorganisms may be affected by toxic material because of the little dilution of the inflow. Discouraging the excessive growth of filamentous organisms that can cause settlement problems in the secondary clarifier is the advantage of plug flow AS process [4, 31].

Table 2

The design criteria and operational conditions for processes of MWWTP based on combined TF/AS process

Process or unit	**Design criteria and operational conditions**
Influent pump station	Number of pumps: 2 Type of pumps: constant speed pumps Depth to influent sewer: 4.57 m Static head: 12.19 m
Screening	Cleaning method: mechanically cleaned Mechanically cleaned depth: 0.30 m Width of bars: 0.63 cm Space of bars: 3.81 cm Slope: 30° Shape factor: 2.42 Approach, maximum and average velocities: 0.76, 0.91 and 0.76 m/s, respectively
Grit removal	Type of grit removal: aerated Number of units: 2 Design basis: depth: 1.50 m Current allowance: 1.7 Manning coefficient: 0.035 Particle size: 0.2 mm Specific gravity: 2.65 Volume of grit: 2.99×10^{-5} m^3 grit/m^3 Detention time: 2.5 min Air supply per unit length of tank: 0.27 N m^3/min/m Surface velocity: 0.45 m/s Tank floor velocity: 0.30 m/s
Primary clarification	Type of clarifier: circular Design basis: average flow Surface overflow rate: 40.74 $m^3/(m^2 \cdot d)$ Sidewater depth: 2.74 m Weir overflow rate: 186.3 $m^3/(m \cdot d)$ Specific gravity: 1.05 Underflow concentration: 4 % SS, BOD, COD, TKN and phosphorus removals: 58, 32, 40, 5 and 5 %, respectively
Trickling filter	Solids production rate: 0.65 kg VSS/kg BOD Effluent BOD: 30 mg/dm^3 Hydraulic loading rate: 44 $m^3/(m^2 \cdot d)$ Surface specific area: 85.30 m^2/m^3
Intermediate clarifier and secondary clarifier	Type of clarifier: circular Design basis: average flow Surface overflow rate: 20 $m^3/(m^2 \cdot d)$ Maximum solid loading rate: 117.18 kg/$(m^2 \cdot d)$ Sidewater depth: 3 m Weir overflow rate: 186.3 $m^3/(m \cdot d)$ Specific gravity: 1.03 Underflow concentration: 1 % Effluent SS: 20 mg/dm^3
Conventional (plug flow) AS	Process design: carbon removal plus nitrification Design basis: SRT: 15 d Aeration type: Diffused Bubble size: fine Alpha factor for oxygen transfer in wastewater: 0.5 Beta factor for oxygen saturation in wastewater: 0.95 Fine bubble minimum air flow: 0.61 $dm^3/s/m^2$

Process or unit	Design criteria and operational conditions
	Standard oxygen transfer efficiency: 20 % Mixed liquor suspended solids (MLSS): 2500 mg/dm^3 Maximum heterotrophic specific growth rate: 6 1/d Heterotrophic decay rate: 0.24 1/d Maximum autotrophic specific growth rate: 0.5 1/d Autotrophic decay rate: 0.04 1/d Biomass yield: 0.5
Chlorination	Chlorine dose: 10 mg/dm^3 Contact time at peak flow: 30 min Influent coliform count: 10^7/100 cm^3
Gravity thickening	Design basis: mass loading: 50 kg/(m^2·d) Depth: 3 m Underflow concentration: 5 %
Anaerobic digestion	Specific gravity: 1.05 Percent volatile solids destroyed: 50 % Concentration in digester: 5 % Minimum detention time in primary digester: 15 d Location: Moderate-winter: ~ 0 °C Raw wastewater: 20 °C Digester: 40 °C Fraction of influent flow returned as supernatant: 2 % SS, BOD, COD, TKN and ammonia of supernatant: 6250, 1000, 2150, 950 and 650 mg/dm^3, respectively
Belt-filter press	Cake solids content: 19 % Density of cake: 1200 kg/m^3 Operating schedule per day: 8 h/d Days operating per day: 5 d/week Hydraulic loading per meter of belt press width: 381 m^3/d Polymer dosage: 1 % dry wt. Filtrate solids concentration: 100 mg/dm^3
Hauling and land filing	Disposal cost basis: sludge disposal per ton Distance to disposal site: 20 km Daily operation: 8 h Loading time per vehicle: 0.75 h Hauling time per trip: 1 h

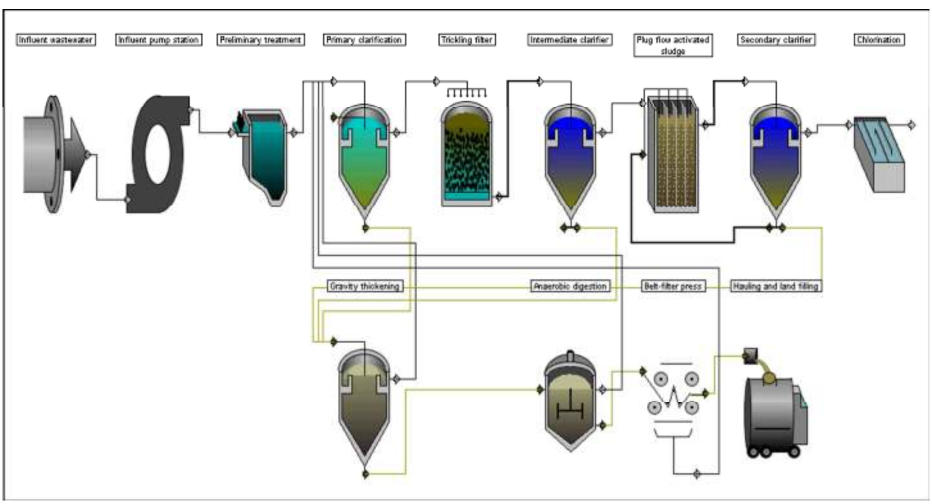

Fig. 1. Layout of MWWTP based on combined TF/AS process

Layout of MWWTP based on combined TF/AS process is shown in Figure 1. The proposed plant consists of influent pump station, preliminary treatment (screening, grit removal), primary clarification, TF, intermediate clarifier, conventional (plug flow) AS, secondary clarifier, chlorination, gravity thickening, anaerobic digestion, belt-filter press, and hauling and land filing. The design criteria and operational conditions used in this study for different treatment processes in MWWTP are shown in Table 2. CapdetWorks uses the influent characteristics and the process parameters to design the applicable system. The designs created by CapdetWorks (typical suggested values) without modification were accepted for all other physical parameters that have not been given here. In reality, the preliminary design (estimated/suggested values) in the "Design Override" tab of the software for all other physical parameters of all unit operations were accepted and used for the cost estimation.

MWWTP based on combined nitrifying trickling filter/activated sludge (NTF/AS)

NTFs are reliable and cost-effective systems to convert NH_3-N [26]. Organic loading, hydraulic loading, temperature, pH, dissolved oxygen concentration, and filter media, etc. are different factors which can affect the kinetics of nitrification [31]. NTFs with 6-12.2 m modular plastic media depths have been reported to have good performance and there are NTFs with depths up to 13 m as well. For maximizing NH_3-N concentration (i.e., maintain a high driving force), recirculation should be reduced to control the biofilm thickness. The rate of nitrification is proportional to the surface area of the media exposed to the liquid being nitrified [26, 32].

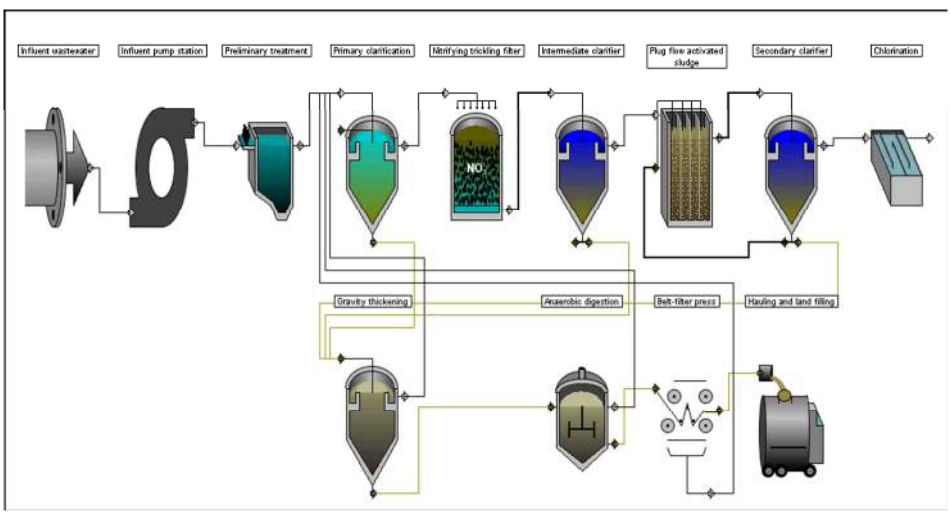

Fig. 2. Layout of MWWTP based on combined NTF/AS process

Layout of MWWTP based on combined NTF/AS process is shown in Figure 2. The proposed plant consists of influent pump station, preliminary treatment (screening, grit removal), primary clarification, NTF, intermediate clarifier, conventional (plug flow) AS, secondary clarifier, chlorination, gravity thickening, anaerobic digestion, belt-filter press, and hauling and land filing. The design criteria and operational conditions of all processes except NTF were the same as those of MWWTP based on combined TF/AS process. Specific surface area, surface loading rate, influent alkalinity, effluent ammonia in summer and effluent ammonia in winter of NTF unit were 134.51 m^2/m^3, 44 $m^3/(m^2 \cdot d)$, 300 mg/dm^3, 2 mg/dm^3 and 5 mg/dm^3, respectively. The preliminary design (estimated/suggested values) in the "Design Override" tab of the software for all physical parameters of all unit operations without modification were accepted and used for the cost estimation; which values of some physical parameters of some unit operations in this plant were not equal to those of MWWTP based on combined TF/AS process.

Economic analysis technique

The planning level design and costing productivity are remarkably improved by economic analysis and evaluations which result in better engineering decisions. Cost estimation to build, operate and maintain the MWWTPs was conducted using CapdetWorks v4.0 (purchased for academic use) with equipment costing database Sept 2007 (USA, Avg). CapdetWorks designs each unit process in a given process layout based on the influent characteristics and then estimates the cost of the design. It calculates all the cost - capital, operating, energy, material, chemical, amortization and maintenance for each treatment alternative [4, 33]. The program applies two cost estimating methods, parametric and unit costing [24, 34]. The default cost data (the unit costs, cost indices, site-specific costs, and equipment costs) in the software was used for the cost estimation.

Results and discussion

Performance of the MWWTPs based on TF/AS and NTF/AS processes

The MWWTPs based on TF/AS and NTF/AS processes were simulated through the CapdetWorks v4.0 software and final treated effluent characteristics for these plants are given in Table 3. Note that the aim of this study was not to investigate the performance and effect of operational parameters on the performance of these MWWTPs. These values were results of CapdetWorks software and the purpose of reporting these values was to show that the economic comparison of these MWWTPs was assumed based on these final treated effluent parameters. As shown in Table 3, the final treated effluent parameters of the MWWTP based on NTF/AS processes were better than those of MWWTP based on TF/AS processes; and treated effluent investigated parameters from both MWWTPs complied with the regulated treated effluent standards. Amount of ammonia in treated water from the MWWTP based on TF/AS process and the MWWTP based on NTF/AS process were 1.38 and 1.29 mg/dm^3, respectively; which were lower than standard value of about 2 mg/dm^3 (the maximum concentration of ammonia and ammonia compounds allowed for the fish at a temperature of 18 °C and pH of 5-7) [1, 12]. Drewnowski et al. [25] studied the effect of the improvement performed at a large-scale WWTP by means of modeling works and reported the rate of the main processes depending on the aeration, that is oxygen uptake rate (OUR) and ammonia uptake rate (AUR), to be about 22 g $O_2/(kg\ VSS \cdot h)$ and 2.9 g $N/(kg\ VSS \cdot h)$, respectively [25].

Table 3

Results of the software for the final treated effluent characteristics of the MWWTPs based on TF/AS and NTF/AS processes

Parameter	MWWTP based on TF/AS	MWWTP based on NTF/AS	Effluent guidelines [35]
SS [mg/dm^3]	20	20	50
Volatile solids [%]	73.4	34.6	
Settleable solids [cm^3/dm^3]	0	0	
BOD_5 [mg/dm^3]	4.62	3.63	30
Soluble BOD_5 [mg/dm^3]	2.02	2.02	
COD [mg/dm^3]	25.1	13.4	125
Soluble COD [mg/dm^3]	3.04	3.04	
TKN [mg N/dm^3]	2.84	1.98	
Soluble TKN [mg N/dm^3]	1.38	1.29	
Ammonia N [mg N/dm^3]	1.38	1.29	
Nitrite [mg N/dm^3]	0	0	
Nitrate [mg N/dm^3]	30.8	26.6	
Total phosphorous [mg P/dm^3]	0.30	0.10	2
pH	7.6	7.2	6-9
Oil and grease [mg/dm^3]	0	0	10

Economic comparison of the MWWTPs based on TF/AS and NTF/AS processes

The total project construction cost ($) and the total operation, maintenance, material, chemical, energy, and amortization costs ($/year) of the MWWTPs based on TF/AS and NTF/AS processes are shown in Figure 3 and Figure 4, respectively. The software designs each unit process in a given process layout based on the influent characteristics and then estimates the cost of the design. Note that these values were results of CapdetWorks v4.0 software for large-scale MWWTPs with mean influent flow of 15000 m^3/h. In addition, for the influent characteristics in this study and compliance of treated effluent parameters from both MWWTPs with the regulated treated effluent standards, estimated/suggested values in the software for physical parameters of some unit operations of these plants were not identical. For example, based on the design created by software (suggested/estimated values in the software), number of stages of TF was 2 and physical parameters (diameter, depth, etc.) of TF and NTF were not identical. Furthermore, the aim of this study was not to optimize the costs of these plants with changing physical and operational parameters; but, the purpose of this simulation was only the simple comparison of their costs based on acceptable designs. Figure 3 illustrates that the project construction cost of the MWWTP based on TF/AS was higher than that of the MWWTP based on NTF/AS by about 15.25 % under the used design criteria and operational conditions in this study. Also, Figure 4 shows that all the total operation, maintenance, material, chemical, energy, and amortization costs of the MWWTP based on NTF/AS were lower than those of the MWWTP based on TF/AS. All the costs of the NTF were lower than those of the TF. One benefit of applying NTF is reduced sludge yield [24]. The reduced sludge yield and resulting low total suspended solids concentration in the NTF effluent stream may lead to decreased costs for downstream units (e.g. intermediate clarifier and plug flow AS) and sludge treatment sections (gravity thickening, anaerobic digestion, belt-filter press, and hauling and land filing). An analysis in the software demonstrated that all costs for both plants are reduced with decreasing the selected design influent flow rate. These results depicted that the MWWTP based on

NTF/AS was cost effective and the material and amortization costs for both plants were higher in comparison with the operation, maintenance, energy, and chemical costs.

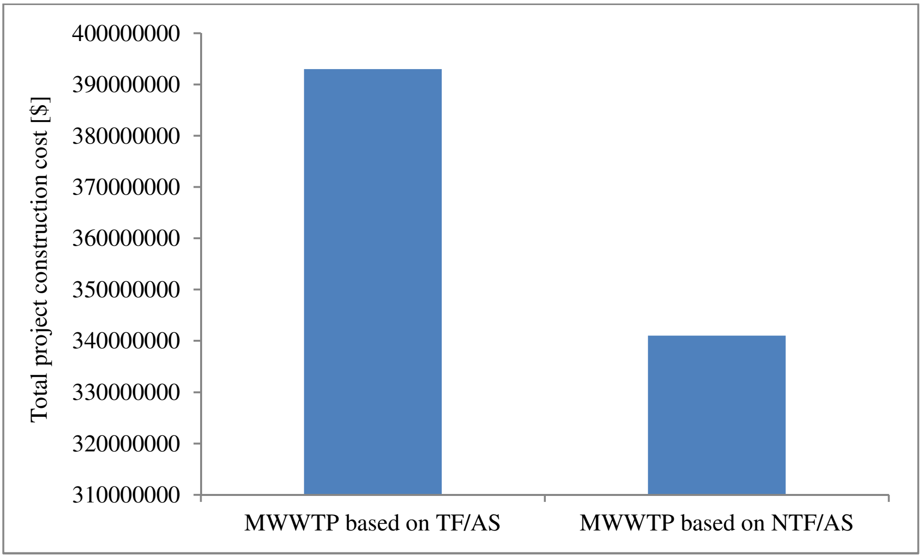

Fig. 3. Results of the software for the total project construction cost of the MWWTPs based on TF/AS and NTF/AS processes for the influent flow rate, design criteria and operational conditions used in this study

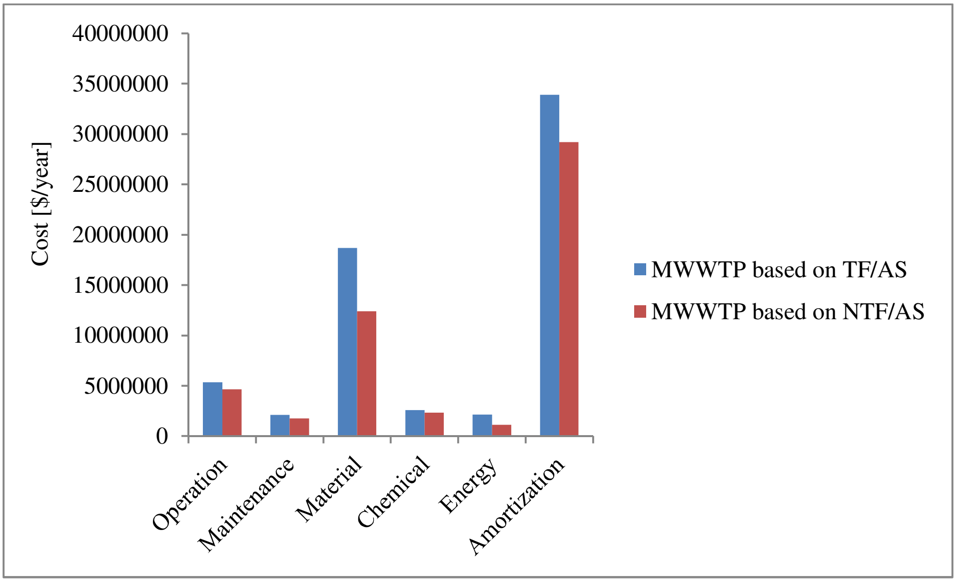

Fig. 4. Results of the software for the total operation, maintenance, material, chemical, energy, and amortization costs of the MWWTPs based on TF/AS and NTF/AS processes for the influent flow rate, design criteria and operational conditions used in this study

Conclusions

Combined NTF/AS was suggested for the modernization of a MWWTP and the performance and economics of MWWTPs based on the combined TF/AS process and combined NTF/AS process were simulated and compared:

- Amount of ammonia in treated water from the MWWTP based on TF/AS process and the MWWTP based on NTF/AS process were 1.38 and 1.29 mg/dm^3, respectively; which were lower than standard value of about 2 mg/dm^3 (the maximum concentration of ammonia and ammonia compounds allowed for the fish at a temperature of 18 °C and pH of 5-7).
- Under the used design criteria and operational conditions in this study, the project construction cost of the MWWTP based on TF/AS was 15.25 % higher than that of the MWWTP based on NTF/AS.
- One benefit of applying NTF is reduced sludge yield. The reduced sludge yield and resulting low total suspended solids concentration in the NTF effluent stream may lead to decreased costs for downstream units (e.g. intermediate clarifier and plug flow AS) and sludge treatment sections (gravity thickening, anaerobic digestion, belt-filter press, and hauling and land filing). Thus, the MWWTP based on NTF/AS can be cost effective.
- Under the used design criteria and operational conditions in this study, the material and amortization costs for both plants were higher in comparison with the operation, maintenance, energy, and chemical costs.
- Note that this study is a computer simulation for a case based on acceptable designs and drawing general conclusions only on the basis of this computer simulation may be insufficient.

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