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Economic comparison between wastewater treatment systems using simulation software

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ABSTRACT

Cost estimation may affect selection of wastewater treatment plant technology. The aim of this research is to determine the optimum wastewater treatment plant (WWTP) technology among performance convergent technologies that utilize a small footprint and comply with environmental Egyptian regulations, with a focus on their economic cost. Three wastewater treatment technologies: intermittent cycle extended aeration system (ICEAS), moving bed biofilm reactor (MBBR) and complete mix activated sludge (CMAS) were proposed, and simulated using GPS-X and CapdetWorks software to predict performances, calculate and compare the capital, operation and maintenance costs for them. The GPS-X simulation results for the three technologies performance proved that all these technologies can achieve effluent concentrations that comply with environmental Egyptian regulations. CapdetWorks cost estimation results demonstrated that; ICEAS aeration tank construction cost was higher than MBBR and CMAS technologies, and despite, that the MBBR aeration tank having a lower volume, the construction of CMAS system aeration tanks was less in cost (13.5% less), but the construction cost of MBBR's gravity thickeners and drying beds was less expensive than ICEAS and CMAS systems. The total construction cost was 19.6, 17.1 and 17.7 M \$ and the operation and maintenance costs were 1.8, 1.5 and 2.1 M \$/y, for ICEAS, MBBR and CMAS WWTPs, respectively. The operation and maintenance of drying beds represented 59%, 40% and 58% of the total operation and maintenance costs for ICEAS, MBBR and CMAS technologies respectively. MBBR technology WWTP is considered most cost-effective and more economic, where the price of 1 m^3 was 0.47, 0.39 and 0.48 \$ for ICEAS, MBBR and CMAS technologies respectively.

Keywords: Cost estimation; Intermittent cycle extended aeration system (ICEAS); Moving bed biofilm reactor (MBBR); Complete mix activated sludge (CMAS); GPS-X; CapdetWorks

1. Introduction

The municipal wastewater contains carbon, nitrogen, phosphorus and sulfur [1]. The treated wastewater effluent contains large amounts of carbon, nitrogen and phosphorus which cause eutrophication of water bodies when received by these water bodies [2]. Most environmental legislations in the world were put to control and protect the environment against treated wastewater, as well as other environmental pollutants [3]. In Egypt, law 48/1982 is regulating the treated wastewater disposal in the different water bodies. Also, the Egyptian code of practice no 501-2005 for the reuse of treated wastewater in irrigation determined that the reuse of treated sewage in agriculture should be according to the quality of water. Table 1 summarizes the local regulation in Egypt, which protect the surface water. The Egyptian regulation doesn't consider ammonia, total nitrogen and total phosphorus removals yet. In Egypt, in most cases, the project of the wastewater treatment plant is flexible to be constructed with any type of wastewater treatment technologies, but in case of limited available area, any technology that has less footprint could be constructed, without doing further economic comparison study between these technologies. The wastewater treatment plant (WWTP) construction, operation and maintenance costs depend on the required treatment level of raw wastewater to comply with environmental regulations [4] so, the comparison is made in this study to get the optimum WWTP technology concerning the economic cost to comply with environmental Egyptian regulation.

Cost estimation is carried out during the project feasibility study and may affect the selection of wastewater treatment plant technology. The most economical cost must be selected from among well-costed alternatives based on an accurate design [5]. For an economical cost comparison, the cost of wastewater treatment plants must include the capital cost in addition to operation and maintenance costs. A calculation can assist in cost evaluation for treatment plants [6]. The computer modeling programs have become popular in the design and simulating the wastewater treatment plant process [7]. The modeling can easily predict system treatment performance [8,9]. Also, the cost estimation program was used for both capital and operating cost and it provides the appropriate cost for the WWTP [10].

Various authors used model simulation to evaluate and predict performance activated sludge wastewater including ICEAS, moving bed biofilm reactor (MBBR), complete mix activated sludge (CMAS) and others processes technologies [11–13], but the cost analysis for these technologies was constricted, for instance Abbasi et al. [14] evaluated three configuration of conventional activated sludge economically based on change raw wastewater quality. Arif et al. [15] compared economically between three treatment; conventional activated sludge with and without denitrification and membrane bioreactor plants. Hunter et al. [16] proved that the cost of energy for treat municipal wastewater was less in wetland than conventional treatments. Piotrowski et al., Simon-Várhelyi et al. and Zadorojniy et al. [17–19] tried to reduce the operation cost of wastewater treatment. Jiang et al. [20] formularized economically relation based wastewater treatment plants capacity. Li et al., Mirabi et al. [21,22] compared upgrading alternatives of the treatment plant based on economic options. The other researchers conducted same manner in their studies, they discussed the technologies with varying efficiencies and optimized operation parameters in absence of technologies rapprochement in performance such as ICEAS, MBBR and CMAS technologies.

As discussed early, limited research papers are referring to the economic comparison between the wastewater treatment systems, regardless of converge systems performance in wastewater contamination removal. Different from literature research, this study aims to present the economic comparison between ICEAS, MBBR and CMAS technologies as systems that have a small footprint, and determine the optimum WWTP technology concerning suspended solids and organic matter removals.

Table 1
Environmental Egyptian regulation

Parameter, mg/L	Local regulation limits	
	Decree 48/1982[a]	ECP, 501-2005[b]
COD	80	80
BOD_5	60	40
TSS	50	40

[a]Discharge to brackish water;
[b]Second group (advanced treatment).

2. Materials and methods

2.1. Wastewater characteristics

The influent wastewater for selected WWTPs technology used in this study, is real municipal wastewater of the existing El-Delngat WWTP. The influent samples of El-Delngat WWTP were collected and characterized two times per week for months March and April 2021, using National Research Center Lab Staff. Table 2 summarizes the characteristics of the wastewater that was used during this study.

2.2. Wastewater treatment technology

The existing El-Delngat WWTP is an extended aeration activated sludge system. As shown in Fig. 1, it consists of preliminary headworks, two oxidation ditches and two final sedimentation tanks in addition to a chlorine contact tank and sludge treatment facilities. El-Delngat WWTP is located at X = 262327 m, Y = 3416472 m and Z = 4.0 m. The existing El-Delngat WWTP design capacity is 10,000 m^3/d, and due to the increase of incoming flow, it is decided to extend the plant to receive 20,000 m^3/d at the area of the extension, located beside the old plant. Due to the area limitation of the extension plant (about 6.0 acres), the proposed treatment system for the extension plant is one of the following technologies: ICEAS, MBBR and CMAS systems [6,23,24].

ICEAS is a modification of a conventional sequencing batch reactor (SBR) system, in which the system is operated under continuous flow [11]. ICEAS consists of two chambers separated by a baffle wall (pre-react and main react zones) and the cycle steps consist of react, settling, decanting and wasting phases [25]. MBBR is attached growth system and it was developed to utilize moving carriers to overcome the problems of fixed media [26]. CMAS is like the conventual activated sludge system with modification in the aeration tank to achieve good mixing and uniform food/microorganisms ratio [25].

Table 2
Characteristics of influent wastewater in this study

Items	Average (mg/L) ± SD	Design (mg/L)
COD	913 ± 112	900
BOD_5	512 ± 59	500
TSS	611 ± 92	600
VSS	438 ± 64	450
NH_4–N	48 ± 11	50
NO_2–N	0 ± 0	0
NO_3–N	0 ± 0	0
TN	77 ± 15	80
TP	9 ± 3	10

2.3. Design of wastewater treatment plant alternatives (ICEAS, MBBR and CMAS)

The design capacity of the extension plant is 20,000 m^3/d and it is supposed to be used for treating the flow until 2037. The design calculation for sizing the wastewater plant is conducted according to formulas and guidelines in the textbooks [25,27,28]. The design is conducted for the three wastewater treatment technologies; ICEAS, MBBR and CMAS to achieve an effluent quality compliance with environmental Egyptian regulation law 48/1982 and ECP, 501-2005 for chemical oxygen demand (COD), biochemical oxygen demand (BOD_5) and total suspended solids (TSS) parameters.

2.4. Verification of the design guideline using mathematical modeling

Various authors used model simulation to study activated sludge wastewater treatment plants [8,11,12,14,29,30]. Among available commercial modeling software, GPS-X simulator V 8.0 (Hydromantis Environmental Software Solutions, Inc., Canada), which is one of the popular modeling software. GPS-X simulator contains IWA's activated sludge models and Hydromantis's models [31]. The simulation was conducted using GPS-X simulator V 8.0 for ICEAS, MBBR and CMAS systems to verify the manual design and to emphasize process performance.

The simulation results for runs were obtained using a default kinetics parameter of Mantis2 model. As shown in Figs. 2–4 the model construction in GPS-X is comprised of wastewater influent, equalization tank, sedimentation tanks, biological unit, wastewater effluent.

2.5. Wastewater treatment plants cost analysis

Using software programs has become popular in cost estimation, one of these programs is the CapdetWorks program which calculates capital and operation and maintenance costs for WWTPs [32]. Various authors used CapdetWorks

Fig. 1. El-Delngat WWTP and its extension location.

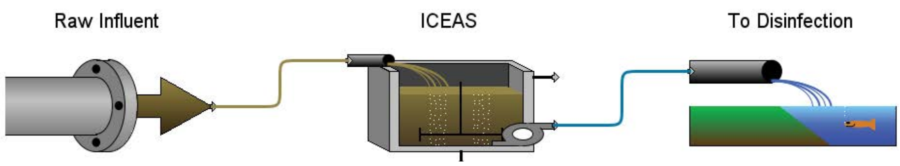

Fig. 2. El-Delngat WWTP ICEAS layout in GPS-X simulator.

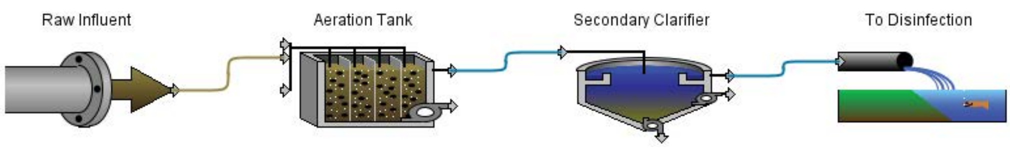

Fig. 3. El-Delngat WWTP MBBR layout in GPS-X simulator.

cost estimate model to compare and predict wastewater treatment plants cost [5,14,15,21,30,33,34]. CapdetWorks V 4.0 was used in this study to build the ICEAS, MBBR and CMAS technologies and calculate the capital, operating and maintenance costs for the WWTPs alternatives. The input data in CapdetWorks for ICEAS, MBBR and CMAS WWTPs units (Dimensions, shapes, removal, etc.) was according to the GPS-X models. Figs. 5–7 show model construction in CapdetWorks for ICEAS, MBBR and CMAS.

3. Results and discussions

3.1. Performance of wastewater treatment technologies (ICEAS, MBBR and CMAS) by GPS-X model simulation

The simulation of ICEAS, MBBR and CMAS plants in GPS-X simulator V 8.0 was carried out in order to predict the performance of the three technologies in terms of TSS, COD, BOD_5, total nitrogen (TN) and total phosphorus (TP) removals. The simulation results of TSS, BOD, COD, TN and TP effluent concentrations were 30, 21, 58, 56 and 3.8 mg/L, respectively for ICEAS technology, 43, 27, 73, 48 and 6.9 mg/L, respectively, for MBBR technology and 54, 26, 75, 42 and 4.9 mg/L, respectively, for CMAS technology, as shown in Fig. 8.

The TSS removal was 95%, 92.8%, 91.0%; BOD_5 removal was 95.8%, 94.6% and 94.8%; COD removal was 93.6%, 91.9% and 97.2% for ICEAS, MBBR and CMAS technologies respectively. The model results proved no significant difference between the three technologies performance for TSS, BOD_5 and COD ($P > 0.05$, one-way ANOVA by SPSS V25) except that there was a minor difference between MBBR and CMAS technologies for COD removal.

The models results show that the ICEAS, MBBR and CMAS are capable to achieve effluent concentration that complies with environmental Egyptian regulation in terms of TSS, BOD and COD.

The retention time was 3 h and 5 h for MBBR and CMAS technologies as reported in the design guideline [25,27,28].

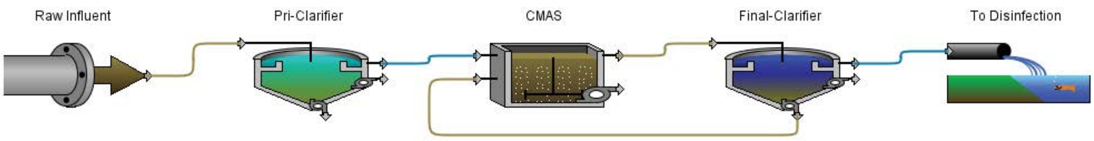

Fig. 4. El-Delngat WWTP CMAS layout in GPS-X simulator.

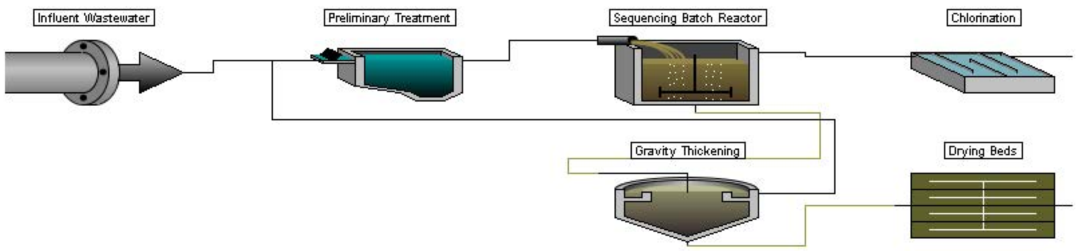

Fig. 5. El-Delngat WWTP ICEAS layout in CapdetWorks.

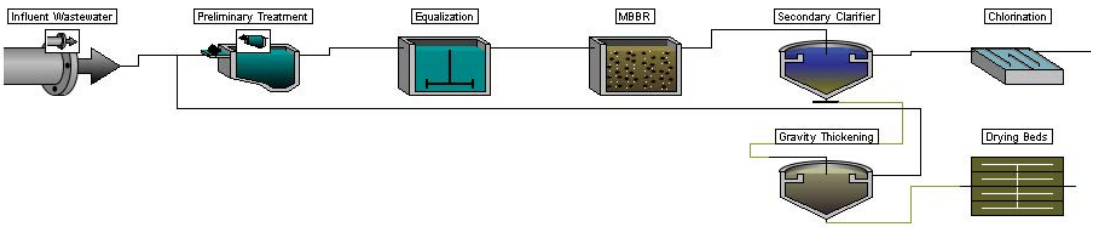

Fig. 6. El-Delngat WWTP MBBR layout in CapdetWorks.

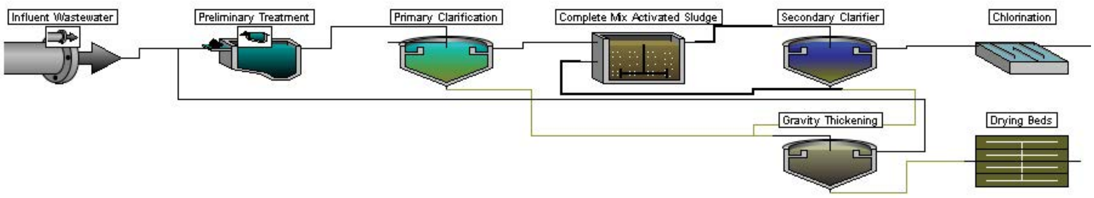

Fig. 7. El-Delngat WWTP ICEAS layout in CapdetWorks.

ICEAS is able to treat wastewater at a retention time of 14 h and produce good effluent quality [35,36].

3.2. Economical comparison between wastewater treatment technologies as a function of capital costs

CapdetWorks was used for estimation and analysis of the capital, maintenance and operational costs for ICEAS, MBBR and CMAS WWTPs. The total project construction cost ($) was illustrated in Fig. 9, for ICEAS, MBBR and CMAS WWTPs technologies. The project construction cost is a sum of unit process costs.

The preliminary treatment cost of MBBR technology was higher than the other two technologies due to the cost of fine screens in the MBBR technology. The fine screen is needed in MBBR process flow to prevent blockage of carrier media [25].

The ICEAS aeration tank cost was higher than the other two technologies due to increasing tank volume, despite that the MBBR aeration tank is a lower aeration tank volume, the aeration tank volume of CMAS cost is lower by 13.5%. The reason for this cost, is increasing the cost of equipment and media in the MBBR technology system [27].

In the CMAS WWTP technology, the construction cost of gravity thickeners and drying beds were higher than MBBR and ICEAS WWTPs technologies and MBBR technology had the lower cost value. The reason for the variation of sludge treatment cost in the three WWTP technologies

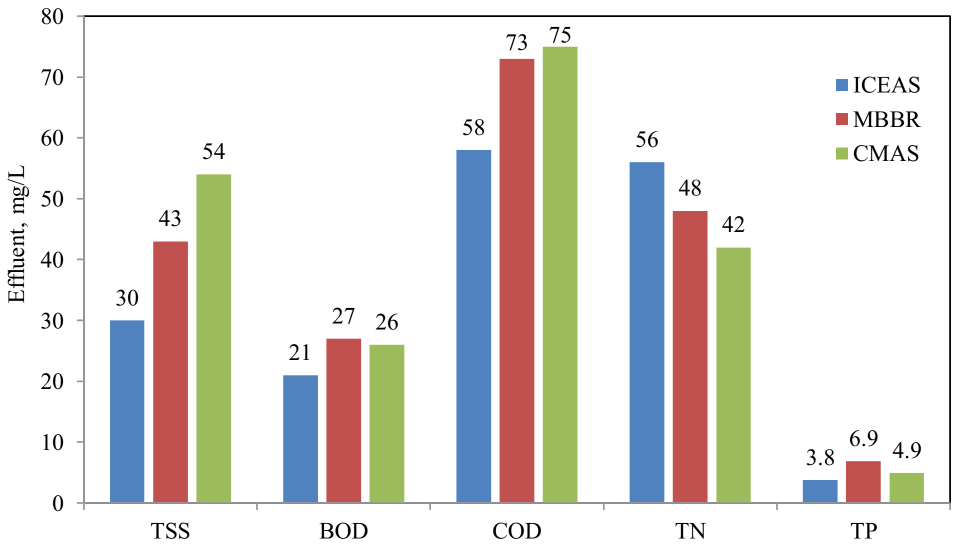

Fig. 8. Comparison of wastewater effluents for ICEAS, MBBR and CMAS technologies.

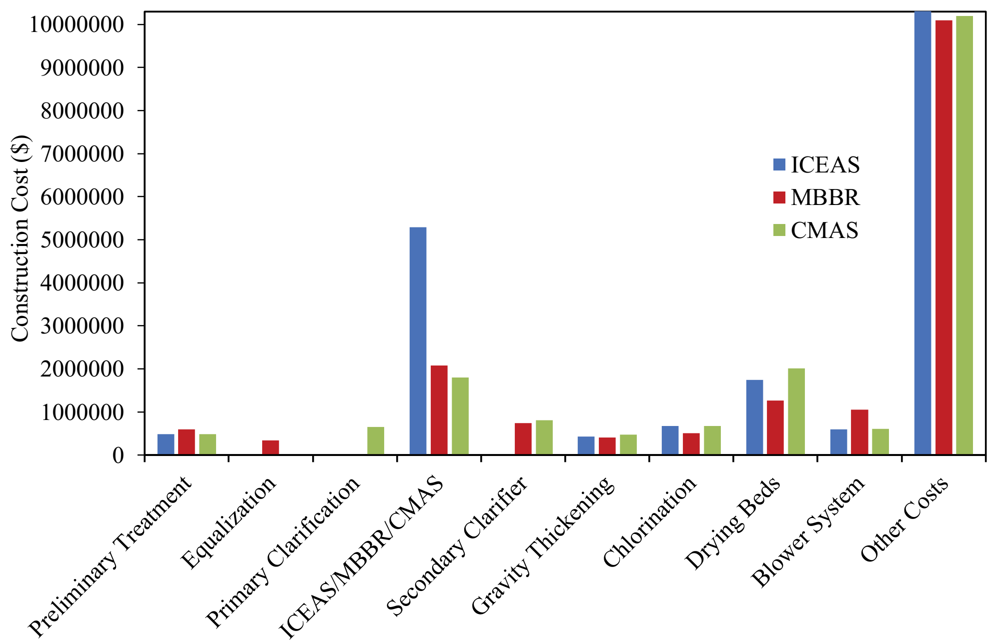

Fig. 9. Construction cost comparison of ICEAS, MBBR and CMAS technologies.

was ascribed to the amount of sludge generated from the system [37]. CMAS technology generates sludge > ICEAS technology > MBBR technology, even if the three technologies have the same sludge process flow, the amount of generated sludge from each system impacts the size of sludge treatment units and CMAS had a greater units size as described in Table 3 then ICEAS technology, and finally MBBR technology.

The variation in the construction of the blower system between the MBBR and the other two systems of WWTP technologies may be ascribed to the higher airflow required in the MBBR system [25,38].

The other costs include mobilization, site preparation, site electrical power cost, yard piping, instrumentation and control, lab and administration building, land, design fee, inspection, interest during construction costs and profit [15,33]. The variation in the construction of the other costs is less than 1% between the technologies and not considered a cost probability, of the higher costs. The total construction cost of treatment units was 19.6, 17.1 and 17.7 M $ for ICEAS, MBBR and CMAS technologies respectively, MBBR system has less construction cost compared with ICEAS and CMAS WWTP technologies and the CMAS system technology has less construction cost than ICEAS technology. The lower MBBR technology construction cost may be ascribed to the reduction in its units cost, not the elimination of the process units. The variation between the construction cost of MBBR and CMAS systems technology is less than 5% and it is not considered a significant value ($P > 0.05$).

3.3. Economical comparison between wastewater treatment technologies as a function of operation and maintenance costs

Figs. 10–14 illustrate the operation, maintenance, materials, chemicals, and energy cost comparison of unit processes for three WWTPs alternatives. According to Figs. 10 and 11, the operation and maintenance of drying beds in each system technology have the governing cost for comparison between the system as a function of operation and maintenance costs. The operation cost of drying beds is 750,000, 417,000 and 847,000 $/y corresponding to 56.4%, 38.4% and 56.2% of total annual operation cost for ICEAS, MBBR and CMAS system technologies respectively. Also, the maintenance cost of drying beds is 330,000, 175,000 and 367,000 $/y corresponding to 67.3%, 43.9% and 64.5% of the total annual maintenance cost for ICEAS, MBBR and CMAS system technologies respectively. The operation and maintenance of sludge drying beds are the operation and maintenance labor cost, due to the required quantity in person-h/y for O&M. The default unit cost for labor rate is 51.5$/h in CapdetWorks which is used. Abbasi et al. [14] adjusted default costs of operator labor rate $/h $25.00, while Arif et al. [15] used $ 5.33. The drying beds in WWTP of MBBR system technology were less in the operation and maintenance costs than the other two systems, which means clearly that this reduction was related to the MBBR technology, that have a less sludge production [27].

The ICEAS aeration tank has a higher material cost than the other two systems as depicted in Fig. 12. The chemical cost is related to chlorine used in chlorination of treated wastewater as depicted in Fig. 13, the cost of chlorination in MBBR system is less where the cost of chlorination in MBBR system is based on average flow due to using the equalization tank unlike the ICEAS and CMAS technologies [10].

The major energy cost is used in the aeration tank as depicted in Fig. 14, MBBR aeration tank was a high energy cost where the used aerated diffuser type in MBBR system is coarse bubble diffusers, with less oxygen transfer efficiency compared with the fine bubble diffusers that are used in ICEAS system [38–40]. Also the dissolved oxygen concentration required in MBBR system is higher than ICEAS system [25,27,41,42].

3.4. Summary comparison between wastewater treatment technologies

Table 4 presents the ICEAS, MBBR and CMAS WWTPs project costs, including construction, operation, maintenance, material, chemical and energy costs in addition to amortization of the cost. It is clear that MBBR technology WWTP is the most cost effective compared with the other two technologies of the WWTP.

In order to identify the cost, spend for treating 1 m^3 of raw wastewater, the following equations are used [14].

$$\text{Capital recovery factor}\left(\text{CRF}\right)=\frac{i\left(1+i\right)n}{\left(1+i\right)n-1} \tag{1}$$

$$\text{CRF}=\frac{0.08\left(1+0.08\right)40}{\left(1+0.08\right)40-1}=0.0818,$$

$$\text{annualized project cost}=\text{capital cost}\times\text{CRF} \tag{2}$$

and

$$\text{cost / m}^3=\frac{\begin{pmatrix}\text{annualized project cost}\\ +\text{ annual operation and maintenance cost}\end{pmatrix}}{\left(\text{design flow}\times 365\right)} \tag{3}$$

The price of 1 m^3 assuming an interest rate (i) of 8% and design period (n) of 40 y, is 0.47, 0.39 and 0.48$ for ICEAS, MBBR and CMAS technologies respectively.

4. Conclusions

- The GPS-X simulation results for ICEAS, MBBR and CMAS technologies proved that, these technologies achieve effluent concentration, comply with environmental Egyptian regulation in terms of TSS, BOD and COD.
- CapdetWorks cost estimation results demonstrated that; ICEAS aeration tank construction cost is higher than MBBR and CMAS technologies and despite the MBBR aeration tank having a lower volume, the construction of CMAS system aeration tanks was less cost, (13.5% less).
- The construction cost of gravity thickeners and drying beds in the MBBR plant is less expensive than ICEAS and CMAS WWTPs.

Table 3
ICEAS, MBBR and CMAS technologies facilities and design parameters

Items	Dimensions	ICEAS	MBBR	CMAS	Design parameters	ICEAS	MBBR	CMAS
Inlet chamber	L × W × D, m	4 × 3 × 1.5	4 × 3 × 1.5	4 × 3 × 1.5	Retention time, s	30	30	30
Coarse screen	No.(W × D), m	2(0.8 × 0.5)	2(0.8 × 0.5)	2(0.8 × 0.5)	Velocity through the screen bars, m/s Spacing between bars, mm	0.86 25	0.86 25	0.86 25
Fine screen	No.(W × D), m	–	2(0.8 × 0.8)	–	Velocity through the screen bars, m/s Spacing between bars, mm	– –	1.26 4	– –
Grit removal	No.(L × W × D), m	2(9.0 × 2.5 × 3.0)	2(9.0 × 2.5 × 3.0)	2(9.0 × 2.5 × 3.0)	Surface load rate, $m^3/m^2/d$ Retention time, s	740 290	740 290	740 290
Primary sedimentation tank	No.(Ø × D), m	–	–	2(20 × 4.0)	Overflow rate, $m^3/m^2/d$ Retention time, h	– –	– –	32 3
Aeration tank	No.(L × W × D), m	4(45 × 13 × 5)	2(30 × 10 × 5)	2(20.5 × 20.5 × 5)	SRT, d F/M, kg BOD/kg MLSS OLR, kg BOD/m^3·d MLSS, mg/L Total T, h	5 0.24 0.85 3,500 14.0	Long High 3.3 High 3.0	3.0 0.4 1.5 3,500 5.0
Final sedimentation tank	No.(Ø × D), m	–	2(22 × 4)	2(25 × 3.5)	Overflow rate, $m^3/m^2/d$ Solid load rate, kg/m^2·h	– –	26 –	20 5.0
Chlorine contact tank	No.(L × W × D), m	2(10 × 10 × 2.5)	10 × 10 × 2.5	20 × 10 × 2.5	Retention time, min	18	18	18
Blower building					Air flow for: Grit removal Aeration Equalization, m^3/h	 540 18,966 –0	 540 8,260 816	 540 7,630 –
Equalization tank	No.(L × W × D), m	–	2(30 × 10 × 5)	–	Retention time, h	–	4.1	–
Return sludge pumping station	Flow	–	–	20,000 m^3/d	*R*	–	–	100%
Excess sludge pumping station	Flow	1,014 m^3/d	627 m^3/d	840 m^3/d	–	–	–	–
Thickening tank	No.(Ø × D), m	2(12 × 4.5)	2(11 × 4.3)	2(14 × 3.7)	Solid load rate, kg/m^2·h Retention time, h	36 24	40 31	40 33
Thickened sludge pumping station	Flow	216 m^3/d	150 m^3/d	240 m^3/d	–	–	–	–
Supernatant pumping station	Flow	999 m^3/d	611 m^3/d	815 m^3/d	–	–	–	–
Drying beds	No.(L × W × D), m	96(20 × 6 × 0.15)	67(20 × 6 × 0.15)	107(20 × 6 × 0.15)	Retention time, d	8	8	8

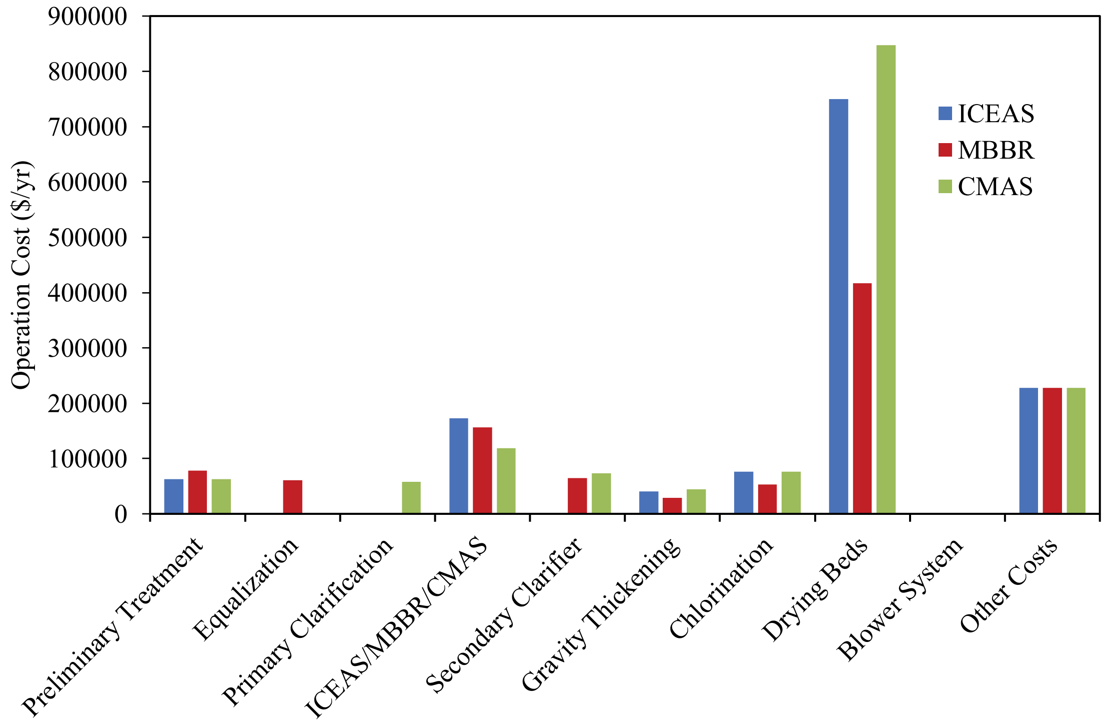

Fig. 10. Operation cost comparison of ICEAS, MBBR and CMAS technologies.

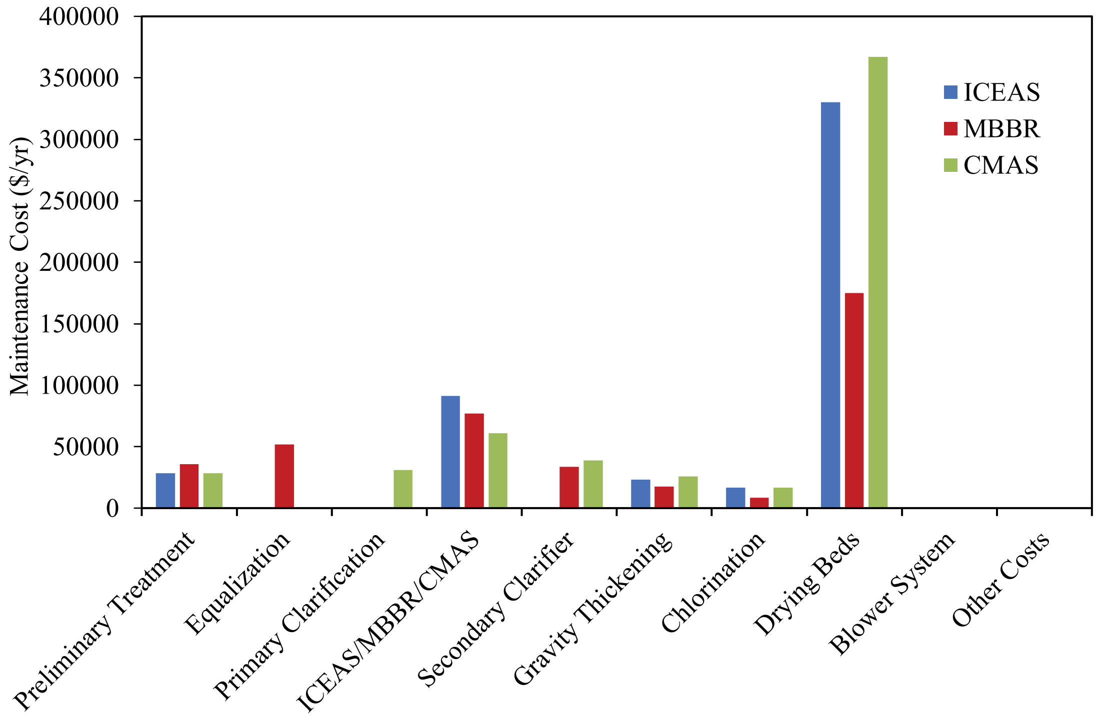

Fig. 11. Maintenance cost comparison of ICEAS, MBBR and CMAS technologies.

- The operation and maintenance costs of drying beds in each system technology are the governing cost for comparison between the systems where it represented 59%, 40% and 58% of the total operation and maintenance costs for ICEAS, MBBR and CMAS technologies respectively and the drying beds in WWTP of MBBR system technology was less operation and maintenance costs than the other two systems.

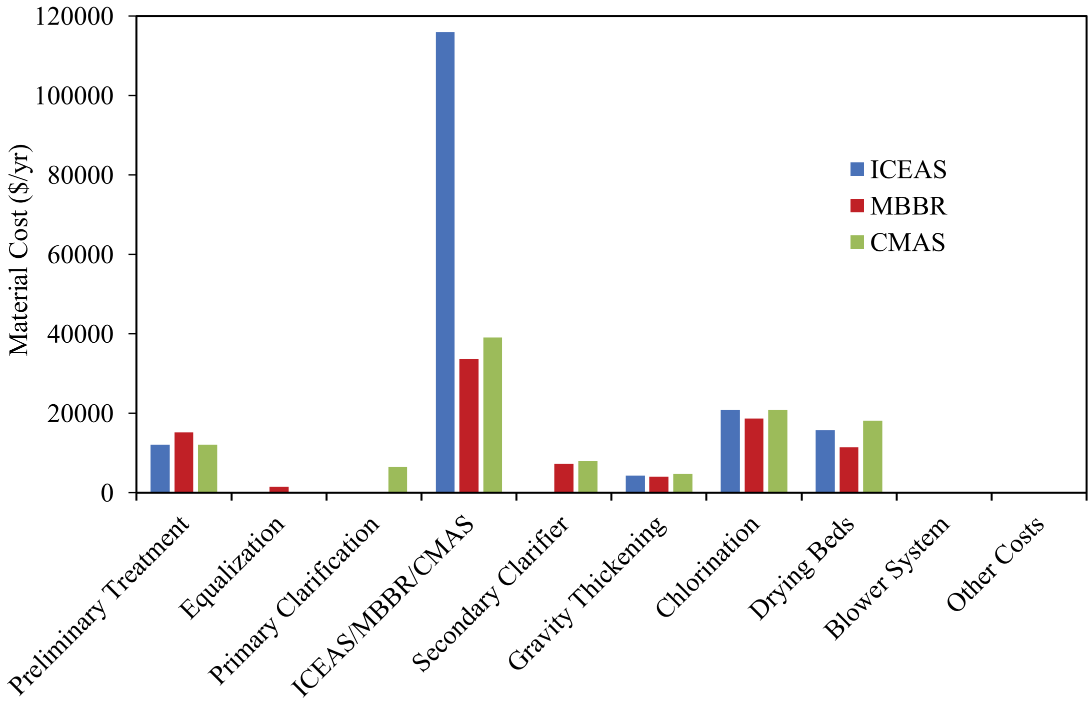

Fig. 12. Material cost comparison of ICEAS, MBBR and CMAS technologies.

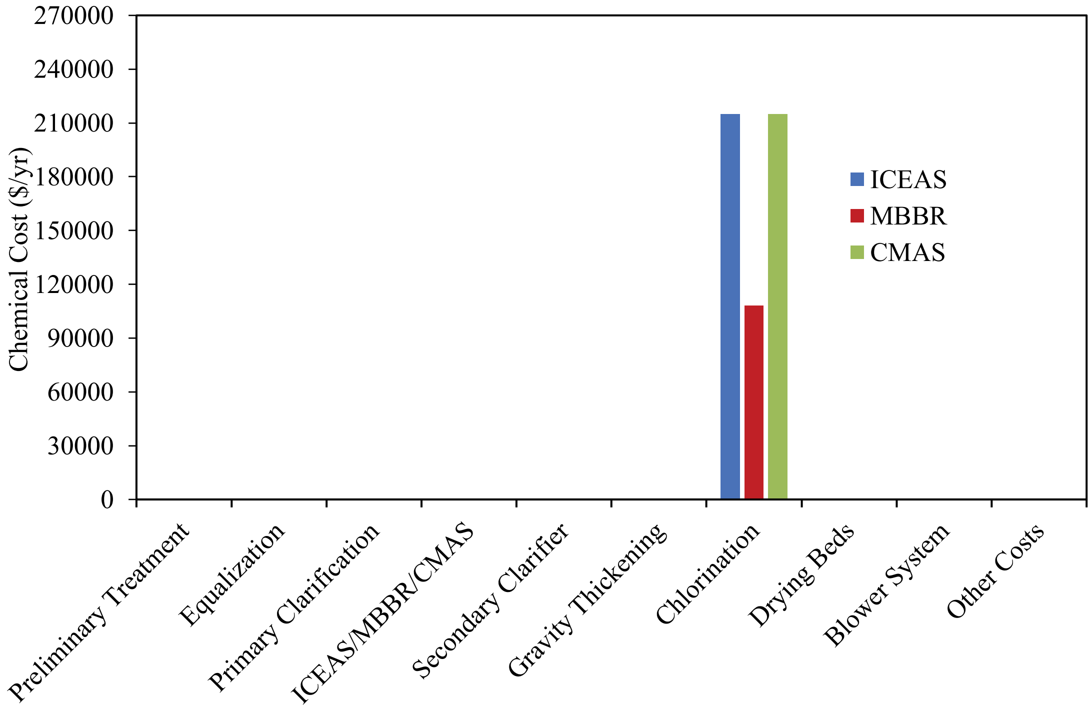

Fig. 13. Chemical cost comparison of ICEAS, MBBR and CMAS technologies.

- The total construction cost was 19.6, 17.1 and 17.7 M $ and the operation and maintenance cost were 1.8, 1.5 and 2.1 M $/y, and the price of 1 m^3 was 0.47, 0.39 and 0.48 $ for ICEAS, MBBR and CMAS technologies respectively for organic matter and TSS removals.
- The process technology played an important role in determining the construction, operation and maintenance costs, MBBR technology WWTP is considered the most effective economical cost compared with ICEAS and CMAS technologies.

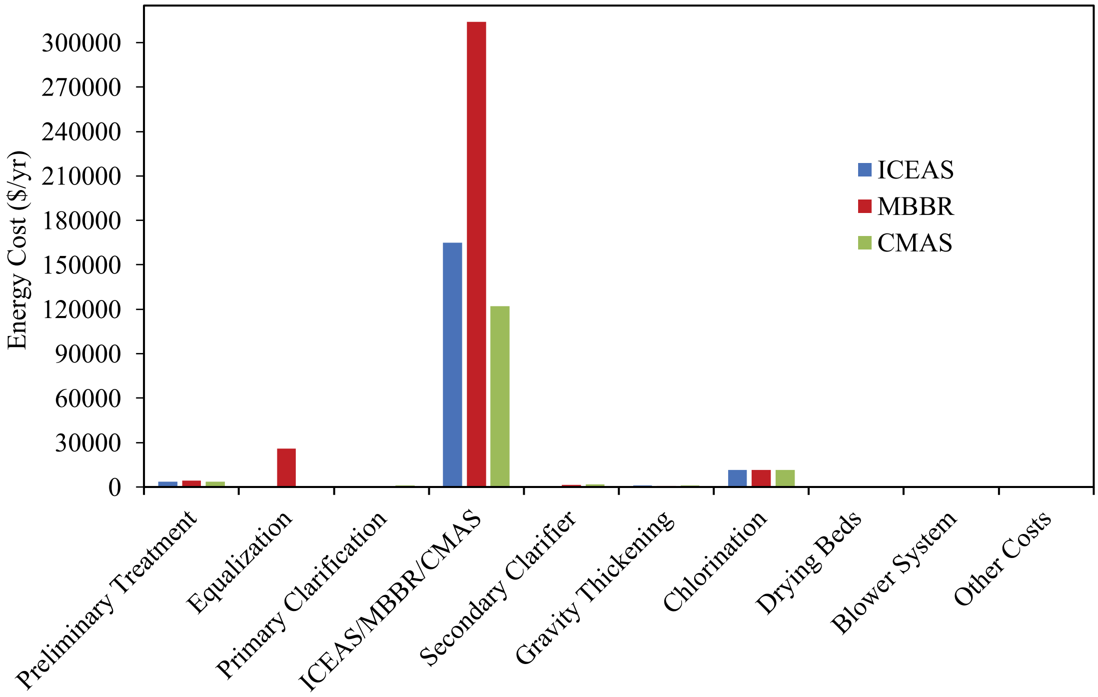

Fig. 14. Energy cost comparison of ICEAS, MBBR and CMAS technologies.

Table 4
Cost comparison between ICEAS, MBBR, and CMAS WWTPs technologies

Layout technology	Construction ($)	Operation ($/y)	Maintenance ($/y)	Material ($/y)	Chemical ($/y)	Energy ($/y)	Amortization ($/y)
ICEAS	19,609,000	1,329,850	490,100	168,910	215,000	180,970	1,693,900
MBBR	17,083,000	1,086,900	398,870	91,615	108,000	358,126	1,452,300
CMAS	17,699,000	1,508,200	568,800	109,040	215,000	140,980	1,505,700

- This study provides the stakeholder with a valuable economic parameter for WWTP technologies and helps in the selection right technologies and focuses on a needed study toward technologies that utilized a small footprint and comply with the regulations.

Declaration of competing interest

Author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contribution statement

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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