# A COMPARATIVE STUDY OF CONVENTIONAL EXTENDED AERATION AND MODERN MEMBRANE BIOREACTOR METHODS OF SEWAGE TREATMENT FROM THE ENVIRONMENTAL AND FINANCIAL PERSPECTIVES

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**ABSTRACT:** The conventional extended aeration (EA) method has been considered as an effective method of secondary wastewater treatment in various installations around the world. The membrane bioreactor (MBR) method has been promoted by membrane manufacturers over the past decade as the most efficient treatment method in the industry. Research has shown the higher quality of MBR effluent compared with that of EA, but the comparison has seldom included the financial aspects. If the effluent quality from both methods is acceptable for a given reuse application, then a major consideration in adopting either method must be financial (i.e., the capital expenditure (CAPEX) and operating expenses (OPEX) involved in their deployment). In this study, simulation of both methods is conducted for domestic wastewater treatment plants using the biological and financial models of CAPDETWorks<sup>TM</sup>. The CAPEX and OPEX findings from the simulation were re-based to October 2019 using global price indices. Hydraulic loads from 500 to 5,000 m<sup>3</sup>/d were considered for three influent strengths: weak, medium, and strong. It is found that the EA method is less costly in meeting the effluent-quality requirements of certain reuse applications, while the MBR is recommended for the extra strong-strength influent especially for units smaller than 500 m<sup>3</sup>/d, due to both effluent quality and lifetime cost.

Keywords: Wastewater treatment, Extended aeration, Membrane bioreactor, Capital expenditure (CAPEX), Operating expenses (OPEX).

# 1. INTRODUCTION

In recent decades, engineered wastewater treatment methods have been progressively developed for various environmental aspects of reuse, such as agricultural, industrial, urban, groundwaterrecharge, etc. [1,2]. These treatment methods could be tailored, through modelling and simulation studies to achieve the required effluent quality with the help of proven, reliable Computer-Aided Design programs. The process of selecting a method to be implemented and the adaptations required in order to comply with a certain environmental criterion of reuse has a financial impact from the CAPEX and OPEX perspectives that need to be considered.

# **1.1 Environmental Aspect**

Extended aeration (EA) is a tested secondary treatment method widely used globally. However, current advances in membrane manufacturing technology make the membrane-based methods increasingly attractive solutions for wastewater reuse applications [3,4]. Mohammadi, Sabzali, Gholami, Dehghanifard, and Mirzaei [5] compared the performance of the EA and MBR methods for the treatment of high-strength wastewater under similar influent conditions, as the Chemical Oxygen Demand (COD) was adjusted in the range of 500 to 2700 and 500 to 5000 mg/L, respectively. The results showed that apart from the better effluent quality in terms of COD, Biochemical Oxygen Demand (BOD<sub>5</sub>), and Total Suspended Solid (TSS) of the MBR method despite its higher organic load, the BOD<sub>5</sub>/COD ratio of the effluent was 0.708  $\pm$ 0.18 and 0.537  $\pm$ 0.106, respectively. This means that more stabilized effluents could also be a benefit of the MBR method of treatment. Meanwhile, the study recommended that special attention be given to cleaning the periodical scaling and biofouling on the MBR membrane due to the high influent strength.

Hatami, Nadali, Roshanaei, and Shokoohi [6] evaluated the possibility of reuse of treated effluents from EA wastewater treatment plant of Bojnoord City, Iran, for agricultural applications. The results showed that the removal efficiency of BOD<sub>5</sub> and COD was 88% and 89%, respectively, with an average residual concentration of 27.0 and 61.0mg/L, respectively. The Chloride and Sodium Adsorption Ratio (SAR) residual values were 3.89 milliequivalents per liter (meq/L) and 221 milligrams per liter (mg/L), respectively. It was concluded that the said effluent could be valuable for agricultural applications, but due to its high chloride

concentration, it has been recommended for semisensitive plants only.

# **1.2 Financial Aspect**

It is clear from the above that very few studies have addressed the relevant CAPEX and OPEX aspects of these treatment alternatives. Some studies have addressed the power consumption per unit flow rate of treated effluents, but only very limited financial comparative studies between the MBR wastewater treatment method and other conventional activated sludge methods, including EA, have been conducted.

Iglesias, Simón, Moragas, Arce, and Rodriguez-Roda [7] compiled the documented data from the public wastewater management institutions in Catalonia and Murcia (ACA and ESAMUR), Spain for fourteen full-scale MBR units and compared them with those installed conventional activated sludge plants. As reported in [7], Spain has one of the highest numbers of MBR-based municipal wastewater treatment plants (WWTPs) in Europe. The results showed that the CAPEX for the treatment plants of a conventional secondary treatment followed by a tertiary treatment of physical, chemical, sandfiltration and disinfection is approximately 30% less than those plants adapted MBR method; but, if the said tertiary treatment is replaced with an advanced membrane filtration (e.g. an ultra-filtration membrane followed by a disinfection unit) to achieve the same quality of the MBR effluent, the CAPEX is approximately 10% higher than that of the MBR plants for capacities less than 10,000 m<sup>3</sup>/d. In terms of the OPEX, the study showed that OPEX is similar for both systems, within the limitations of the study.

There are some limitations of the cited financial comparative study. It did not consider the geographical difference in the cost of the equipment and construction material, nor the monetary value of the land, which represents a significant weight of the CAPEX of both methods, as MBR always requires a smaller foot-print than EA; while the OPEX did not consider the membrane replacement.

# 1.3 Aim and Method of the Study

To address the above limitations and help select the better option of the two methods, especially for decentralized wastewater treatment plants of 500 m<sup>3</sup>/d to 5,000 m<sup>3</sup>/d hydraulic loads, this study's aim is to conduct a detailed environmental and financial comparative assessment of both systems. The environmental aspect is presented by the efficiencyof-treatment for each method in terms of characteristics of the treated effluent, while the financial will be based on the CAPEX and OPEX in USD, considering the updated global market price as of October 2019. The study utilised three different strengths of the influent: weak, medium, and strong.

The method was selected to be of a proven, commercially available nature for the sake of easy replication of the study. Specialized software developers, such as Hydromantis Environmental Software Solutions Inc. (Hydromantis), EnviroSim Associated LTD (EnviroSim), AOUIFAS, etc. have produced powerful mathematical engines capable of running the most sophisticated, implicit mathematical models of wastewater treatment with a minimal discernible error. The same have been presented in the form of software packages (e.g. GPS-X<sup>TM</sup> and BioWin<sup>TM</sup> of Hydromantis and EnviroSim, respectively) that come with various features such as steady-state and dynamic simulations, estimation of chemical and power consumption, etc. Hydromantis has further produced CAPDETWorks<sup>TM</sup>, a software package for the simulation of wastewater treatment plant performance while predicting the life-cycle cost of the same. CAPDETWorks<sup>TM</sup> version 04 2018 is used as a methodological, experimental tool for the subject study. The mathematical models used for both performance simulation and cost estimation are elaborated under 'METHOD'.

# 2. METHOD

# 2.1 Performance Modelling

Henze, Gujer, Mino, and Loosdrecht [8] have developed the Activated Sludge Model No. 1 (ASM1) which is a dynamic wastewater treatment model. ASM1 is adopted by most of the simulation programs (e.g.  $GPS-X^{TM}$  &  $BioWin^{TM}$ ) in their library of Hydromantis According models. to CAPDETWorks<sup>TM</sup> version 04–User's Guide [9], the relevant adapted model is based on the University of Cape Town (UCT) algorithm and is consistent with ASM1. For proper replication, the Solids Retention Time (SRT) shall be substituted with a sufficient time to allow for both biological oxygen removal and nitrification, considering the recommended operating SRT range for both EA and MBR methods, as well as the actual winter temperature and the recommended operating range of the Mixed Liquor Suspended Solids (MLSS). The said model is an accurate preliminary design tool, while for a more detailed design and consideration of dynamic simulation over an extended period of time, GPS-X<sup>TM</sup>, BioWin<sup>TM</sup>, AQUIFAS<sup>TM</sup>, etc., should be used. The 2018 CAPDETWorks<sup>TM</sup> version 04 is used as a computerbased simulation tool for performance modelling. Details of the algorithm for the influent speciation, nitrifier growth/ decay rates, minimum SRT, reactor solid mass, effluent BOD, etc. are elaborated at the CAPDETWorks<sup>TM</sup> version 04-Hydromantis Supplemental Technical Reference [10].

### 2.2 CAPEX and OPEX Modelling

In 1973, the Environmental Engineering Division of the U.S. Army prepared a cost estimation model for wastewater treatment systems for benefit of the U.S. Environmental Protection Agency (EPA). The algorithm was called CAPDET, which stands for process design and estimating algorithms for the Computer Assisted Procedure for Design and Evaluation of wastewater Treatment systems. It was revised in 1982 to overcome the original version's limitation of not reflecting the regional cost differences or accommodating site-specific design requirements [11,12]. Hydromantis has since developed the model further and presented it to the market in a user-friendly software package called CAPDETWorks<sup>TM</sup>. The 2018 version 04 of the said software is used as a computer-based cost estimation tool for life-cycle modelling.

The default unit rate cost of the program's library

can be overridden with available local prices or updated in consideration of globally recognized cost indices that are regularly published in the relevant trade publications, such as Marshall And Swift (MAS), Engineering News Record (ENR), or Chemical Engineering Magazine (CEM). Further, Hydromantis has developed a compilation of cost indices called HECI, HCCI, and HPCI (Hydromantis Equipment Cost Index, Hydromantis Construction Cost Index, and Hydromantis Pipe Cost Index, respectively). For an easy global replication of the study, the local Dubai market prices are not considered, and the compiled cost indices of Hydromantis are considered instead. The same is

updated to October 2019 and kept in USD. Table 1 shows the financial modelling assumptions that shall be revisited on a case-by-case basis. The OPEX over the plant lifetime is converted to its present value, added to the relevant CAPEX and divided by the plant capacity to generate the unit lifetime cost in (/m<sup>3</sup>).



# Fig. 1 Process flow diagram for EA plant

Table 1 Financial modelling assumptions

Items	Assumed Value
Interest rate	8.0%
Construction period	3 years
Operating life of the plant	40 years
Electricity	0.1 USD/kWh
Land cost	20,000 USD/acre
Design and engineering fees	15%
Technical fees	2%
Administration/legal fees	2%
Inspection fees	2%
Miscellaneous	5%
Contingency reserve	10%
Profit and overhead	15%

### **2.3 Simulation Procedures**

#### 2.3.1 Extended aeration method

On the trail to simulate the actual operation of an EA bioreactor, the reactor is placed in a complete plant that treats solid waste as well, as illustrated in Fig.1.

The process flow diagram is summarized as follows:

- Preliminary Treatment: coarse mechanical bar screen followed by an aerated grit and FOG (Fat, Oil & Grease) removal chamber.
- 2- Primary Treatment: a primary clarifier despite some EA plants have shown an acceptable performance without a primary clarifier.
- 3- Secondary Treatment: the core unit of the plant, an EA bioreactor followed by a secondary clarifier with Return Activated Sludge (RAS) and Waste Activated Sludge (WAS) streams to adjust the operating SRT and MLSS.

- 4- Tertiary Treatment: in its simplest form of a multilayer sand filter, which could be in some plants followed by an activated carbon filter, and a disinfection unit of Chlorine Contact Tank (CCT) or Ultra-Violet System (UVS).
- 5- Solids Treatment: a gravity thickener followed by aerobic digester and a belt-filter press, which could also be modified to an anaerobic digester or other sludge dewatering system than the beltfilter press; while various EA plants have reported an acceptable quality of treated solids without gravity thickener due to the relatively well stabilized solids of the EA bioreactor.

### 2.3.2 Membrane bioreactor (MBR) method

In the case of the MBR method, both the aerated bioreactor and the secondary clarifier of the secondary treatment stage are replaced with an aerated membrane bioreactor, which is modelled by an aerated plug-flow tank recycled with a membrane tank in accordance with the CAPDETWorks<sup>TM</sup>, while the tertiary filtration stage is no longer required due to the inherent filtration nature of the membranes. For the sake of equivalent comparison, both the preliminary and solids treatments considered for the MBR plant, while the primary treatment was modified to an equalization tank followed by a fine screen to comply with the recommendations of membrane manufacturers, as illustrated in Fig.2.

#### 2.3.3 Design factors and operating parameters

The design factors are those such as tank dimensions, velocity values, allowable head losses, number of streams, etc, while those such as SRT, MLSS, air flow rate, etc are classified as the operating parameters. For the sake of a traceable replication and to objective focal of the study, the default design factors and operating parameters at CAPDETWorks<sup>TM</sup> database library are considered without change. The same can be overridden to match any other case study as needed.

### 3. RESULTS

#### 3.1 Weak-Strength Influent Case

An influent of 500 m<sup>3</sup>/d is considered as a typical hydrological load for both plants. Table 2 shows higher removal efficiency of the EA method for the biological load in the form of BOD<sub>5</sub> and COD, in addition to better nitrification of the ammonianitrogen (NH3-N) as reflected in the Total Kjeldahl Nitrogen (TKN) than the MBR method, and vice versa for the influent Total Suspended Solids (TSS). Both reactors demonstrated high concentrations of nitrate-nitrogen (NO<sub>3</sub>-N), as the process design did not address denitrification. It worth saying that for proper replication of the study, the actual local environmental conditions, such as relative humidity, temperature, etc. shall be revisited.



Fig. 2 Process flow diagram for MBR plant

Items	Inf. (mg/L)	EA Eff. (mg/L)	MBR Eff. (mg/L)
BOD5	110	0.979	2.2
COD	250	1.47	4.13
TSS	100	8	1
TKN	20	0.095	1.21
NH3-N	12	0.095	1.13
NO3-N	0	15.5	9.1

Table 2 Performance comparison in terms of effluent quality (Eff.) for weak-strength influent (Inf.)

A sensitivity analysis was conducted for a change in hydraulic-load from 500 m<sup>3</sup>/d to 5000 m<sup>3</sup>/d for the same weak-strength influent; two main findings were observed, as shown in Table 3: the dramatic decrease in the cubic meter cost as the plant capacity increases, and the dramatic increase in the difference in the cubic meter cost as the plant capacity increases.

Table 3 Lifetime cost comparison in terms of  $(\text{/m}^3)$  for weak-strength influent (Inf.)

Influent Flow (m <sup>3</sup> /d)	EA Lifetime Cost (\$/m <sup>3</sup> )	MBR Lifetime Cost (\$/m <sup>3</sup> )	Difference in Lifetime Cost (%)
500	24,600	28,000	14%
1,000	13,500	16,200	20%
1,500	9,933	11,933	20%
2,000	8,050	9,850	22%
2,500	6,800	8,480	25%
3,000	5,933	7,567	28%
3,500	5,371	6,943	29%
4,000	4,925	6,625	35%
4,500	4,556	6,178	36%
5,000	4,260	5,920	39%

Attention should be given to the process design itself, as highlighted earlier various installed EA plants have reported an acceptable performance without a primary clarifier, while both the tertiary and solids treatments vary from one plant to another to maintain the required level of compliance with local regulations.

# 3.2 Medium-Strength Influent Case

Like the weak-strength influent case, Table 4 shows that the EA method has a higher reduction in the biological load along with better nitrification, while the MBR method shows better removal of the TSS.

Items	Inf. (mg/L)	EA Eff. (mg/L)	MBR Eff. (mg/L)
BOD <sub>5</sub>	220	0.979	2.2
COD	500	1.47	4.13
TSS	220	8	1
TKN	40	0.095	1.21
NH <sub>3</sub> -N	25	0.095	1.13
NO <sub>3</sub> -N	0	30.7	19.2

The same findings for the weak-strength influent case are noticed with the medium-strength influent case, but with smaller differences in the unit lifetime cost between the two methods, as shown in Table 5.

Table 5 Lifetime cost comparison in terms of  $(\text{/m}^3)$  for medium-strength influent (Inf.).

Influent Flow (m <sup>3</sup> /d)	EA Lifetime Cost (\$/m <sup>3</sup> )	MBR Lifetime Cost (\$/m <sup>3</sup> )	Difference in Lifetime Cost (%)
500	24,800	28,400	15%
1,000	14,300	16,200	13%
1,500	10,400	11,933	15%
2,000	8,550	10,150	19%
2,500	7,360	8,960	22%
3,000	6,467	7,967	23%
3,500	6,029	7,286	21%
4,000	5,575	6,900	24%
4,500	5,156	6,444	25%
5,000	4,860	6,140	26%

# 3.3 Strong-Strength Influent Case

Results were like the weak and medium-strength influent, while the sensitivity analysis shows a much smaller difference in lifetime cost between the two methods as illustrated in Tables 6 and 7 respectively.

Table 6 Performance comparison in terms of effluent quality (Eff.) for strong-strength influent (Inf.)

Items	Inf. (mg/L)	EA Eff. (mg/L)	MBR Eff. (mg/L)
BOD <sub>5</sub>	400	0.979	2.2
COD	1000	1.47	4.13
TSS	350	8	1
TKN	85	0.095	1.21
NH <sub>3</sub> -N	50	0.095	1.13
NO <sub>3</sub> -N	0	68	43.3

Table 4 Performance comparison in terms of effluent quality (Eff.) for medium-strength influent (Inf.)

Influent Flow (m <sup>3</sup> /d)	EA Lifetime Cost (\$/m <sup>3</sup> )	MBR Lifetime Cost (\$/m <sup>3</sup> )	Increased lifetime cost of MBR (%)
500	26,600	28,400	7%
1,000	15,400	17,000	10%
1,500	11,467	12,933	13%
2,000	9,800	10,900	11%
2,500	8,520	9,520	12%
3,000	7,600	8,633	14%
3,500	6,943	7,829	13%
4,000	6,600	7,525	14%
4,500	6,178	7,000	13%
5,000	5,860	6,780	16%

Table 7 Lifetime cost comparison in terms of  $(\text{m}^3)$  for strong-strength influent (Inf.)

The results of sensitivity analysis for the difference in lifetime cost (%) between the EA and MBR of the three cases are represented in Fig. 2.

# 4. DISCUSSION

#### 4.1 Environmental Findings

The results show that the MBR method yields a better effluent quality in terms of TSS (1.0 mg/L) compared to 8.0 mg/L from the EA method, due to its inherent filtration nature of structure, a key merit that introduced the MBR to several reuse-applications, as highlighted in [3]. Meanwhile, the EA method demonstrates a relatively higher removal efficiency for the BOD<sub>5</sub> and COD, and better nitrification than the MBR method, due to the higher SRT of 25.0 days compared to 10.0 days, respectively. The results that

make the study in [6] appreciated the use of EA effluent for the irrigation application for semisensitive plants. It is reasonable to find that the results agree with the study in [5] from the point of efficient removal of both methods for the biological load being treated, while not from the point of a percentage of removal, as the said study was dedicated to the extra strong-strength influent that encountered in special applications where the COD ranges from 500 mg/L to 5000 mg/L with a corresponding SRT of 13 to 34 days, while the subject study considered the usual municipal influent ranges from 250 to 1000 mg/L with a corresponding SRT of only 10 days. Although we can benefit from the inherent advantage of the MBR method of maintaining a high operational MLSS in the bioreactor with minor limitation from the relevant Hydraulic Retention Time (HRT), attention should be given to the disadvantage of the associated production of non-filterable inorganic compounds that could harm the microbial population and/ or the membrane structure, as illustrated in [13].

# 4.2 Financial Findings

The results could be financially interpreted as follows:

- A decrease in the unit cost as the plant hydraulic capacity increases for both methods, as expected.
- A dramatic increase in the difference in the unit cost as hydraulic load increases as concluded in [7].
- The said observed difference in the lifetime unit cost decreases as the influent strength increases, as shown in Fig.2, which makes the MBR more attractive for strong-strength influent, especially for units smaller than 500 m<sup>3</sup>/d, leading to the conclusion that the MBR is not only recommended for the extra-strong influent as concluded in [5], but it is also a cost-competitive than other conventional methods of biological treatment, including the EA.



Fig. 3 Difference in unit lifetime cost for all strengths

### 5. CONCLUSION AND RECOMMENDATIONS

The MBR method of municipal wastewater treatment should not generally be specified for any development project, as the EA method is still an optimum solution economically, which complies with the effluent quality required for some reuse applications, such as irrigation of non-sensitive plants and landscapes. If the MBR's effluent quality is required for a specific area of application, the financial impact of the same should be addressed from the perspective of both CAPEX and OPEX. The MBR method is found to be more attractive for the strong-strength influent, especially for units smaller than 500m<sup>3</sup>/d, and is recommended for the extra strong-strength influent due to both effluent quality and lifetime cost.

For replication of the study, it is recommended that the following points be addressed:

- The local environmental conditions e.g. relative humidity, temperature, altitude, etc. shall be considered.
- If a pilot plant or lab model can be furnished, the actual values of the biological reaction(s) shall be verified accordingly.
- High consideration should be given to the process design (train of treatment) that varies from one plant to another to maintain the required level of compliance with local regulations.
- Globally updated market price indices as of October 2019 are considered to widen the scope of benefit from the study; however, for the sake of accurate monetary values, the local unit prices shall be considered instead.
- The financial modelling assumption should be revisited against the local market and project conditions.

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