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Comparative assessments on wastewater treatment technologies for potential of wastewater recycling

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ABSTRACT

Wastewater recycling plays an important role in minimizing water loss. The recycled wastewater can be utilized for many purposes from irrigation to portable water supply. Numbers of wastewater treatment system have been applied in Malaysia to achieve quality in meeting the intended purpose of wastewater recycling. Although there are many studies reported on the efficiency of the treatment technologies, comparative assessments including the significant purpose until the estimation of operational expenditure for each of the treatment technologies are lacking. Therefore, this brief review aims to critically discuss each of the treatment technologies from the secondary treatments, tertiary treatments, to the advanced treatments. Based on our review, the conventional activated sludge system has high potential for wastewater recycling due to lower cost in terms of population equivalent and shows great removal efficiency among secondary treatment while sand filtration and activated carbon is the better options for tertiary and advanced treatment. Therefore, it can be concluded that conventional activated sludge system, sand filtrations and activated carbon process is the most feasible in terms of removal performance and cost effectiveness for secondary, tertiary and advanced treatments.

Keywords: Wastewater recycling; Wastewater treatment technologies; Comparative assessment

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1. Introduction

Climate changes, the increase in the global population and the development of global economic have caused the increase in the water demand [1,2]. One of the main challenges in this century is the availability of freshwater that meets the standard and the targeted quality. In the past few years, water scarcity issue has received high attention from the public and several indicators have been developed in order to promote the water scarcity status assessment throughout the world [3–8]. Water scarcity refers to the situations which the total demand of water from all sectors could not be met and the water demand level exceeds the level of natural water availability and their supply capacity [9,10]. According to Lee et al. [11], although Malaysia has a large quantity of water resources, water scarcity still happen in some of the regions in Malaysia. Therefore, there is a need to shift for alternative water resources such as wastewater recycling.

The used of recycle and reclaimed wastewater is now becoming more relevant as it will reduce the pressure on the water resources, the discharge of polluted wastewater into the environment and preserving sufficient high quality water resources [12,13]. United States, Australia, Singapore and Belgium are among the countries which have been widely utilizing the recycled or reclaimed wastewater such as the portable water reuse project [14]. However, the challenges associated with the wastewater recycling include potential of pollutant present in the recycled wastewater such as heavy metals, nutrients, pathogens and pharmaceutically active compounds which will affect the human health and the public acceptance on the recycle wastewater [15–18].

The treated wastewater quality should be promising to ensure the feasibility in utilizing the recycled wastewater. The discharge standards used in Malaysia are stipulated in Regulations in Environmental Quality (Sewage), 2009 of Environmental Quality Act, 1974. Standard A is applied to any sewage discharge that is located at the upstream of a public water supply intake point; while Standard B is applied to sewage discharge that is not located at the upstream of the intake point. The permissible limits of biochemical oxygen demand (BOD), total suspended solids, chemical oxygen demand (COD) and NH_3–N value for Standard A are 20, 50, 120, and 5–10 mg/L while for Standard B are 50, 100, 200 and 5–20 mg/L.There are many technologies that can be used in wastewater recycling to achieve the targeted quality such as conventional activated sludge system, extended aeration, sequencing batch reactor, sand filtration, chemical coagulation–flocculation, activated carbon and advanced oxidation process [19].

Therefore, this paper aims to provide comparative assessment between the treatment technologies in terms of operating expenses (OPEX), capital expenditure (CAPEX) and their relative performance and potential for wastewater recycling. Although there are numbers of studies that reported on the performances of the treatment technologies, comparative assessments including the significant purpose until the estimation of operational expenditure (OPEX) for each of the treatment technologies are still lacking. In the end, the comparative assessments of this review may conclude the most feasible wastewater treatment technologies to be used for the potential of wastewater recycling based on its intended purpose.

2. Treatment process

In general, there are different types of wastewater treatment processes that can be applied to achieve the water quality that is required and meet the standards [20]. The treatment processes vary from conventional secondary treatment (i.e., biological oxidation and sedimentation) to advanced treatment such as reverse osmosis (at the extreme side). A sewage treatment plant (STP) mainly comprised of primary and secondary treatment processes. This STP uses physical separation to remove settleable particles and floatable oil and grease, as well as a biological process to remove dissolved and suspended organic compounds in order to achieve a particular level of effluent quality. This is the most commonly used method to treat sewage in Malaysia. Depending on the discharge standard that the treatment plant needs to abide, the discharge wastewater characteristics will vary accordingly. The cost of the treatment process increases from conventional treatment to advanced treatment accordingly. According to Ozgun et al. [21], the cost functions in terms of flow rate or population equivalent (PE) are usually used to assess the operating and investment cost of wastewater treatment system. Table 1 shows the applications and treatment level required for water recycling.

2.1. Secondary treatment

Common types of secondary treatment system that are used in regional or large communal in Malaysia are activated sludge in the form of conventional activated sludge system (CAS), extended aeration (EA) process and sequencing batch reactor (SBR). The activated sludge process can produce a high effluent quality at reasonable operating cost. The recycling of a large proportion of biomass is one of the significant characteristics of activated sludge system which increase the oxidation of organic matter by huge number of microorganisms in relatively shorter time [22]. Lower construction cost and smaller land requirements are also the advantages of the activated sludge system. The activated sludge process is widely used by large cities and communities where large volumes of wastewater must be highly treated economically.

Besides that, extended aeration (EA) process is another type of activated sludge system with extended hydraulic retention times and sludge ages that operates at lower organic loading rates and F/M ratios. EA is usually used without primary settlement and nitrification is normally achieved as it is operated under aerobic condition. EA plants are widely used in wastewater treatment due to its advantages such as varieties in range and capacity [23].

Other than that, the SBR system utilize 5 common steps which is carried out in sequence in a reactor. When filled with wastewater, SBR will works as an equalization basin, which allows the system to withstand peak flows or loads. The advantages of SBR includes smaller footprint and process control abilities which enable it to operate automatically.

Table 1
Applications and treatment level required for water recycling

Treatment level	Increasing level of treatment ►►►		
	Secondary	Filtration and disinfection	Advanced
Process	Sedimentation and biological oxidation	Chemical coagulation, nutrient removal, filtration, and disinfection	Activated carbon, advanced oxidation processes, reverse osmosis, etc.
End use	Orchards and vineyards surface irrigations	Irrigation of golf course and landscape	Indirect potable reuse including groundwater recharge of potable aquifers and surface water reservoir augmentation and potable reuse
	Irrigation of non-food crops	Flushing of toilet	
	Landscape impoundments with restrictions	Washing vehicles	
	Recharge of non-potable aquifer with groundwater	Irrigation of food crops	
	Wetlands restoration, stream augmentation, wildlife ecosystem	Recreational impoundments with no restriction	
	Processes for industrial cooling	Industrial systems	
Cost	Increasing cost ►►►		

2.2. Tertiary treatment

Tertiary treatment (frequently referred to as effluent polishing) is the final cleaning process that involves a series of additional steps to improves wastewater quality before it is reused, recycled, or disposed into the environment. There are great numbers of tertiary treatment processes such as sand filtration and chemical coagulation–flocculation process [22,24]. Lately, several researchers have been focusing on the use of tertiary treatment in compare to conventional treatment in order to achieve better effluent quality in terms of chemicals, pathogens and pharmaceuticals residue [25].

There are three main types of sand filtration system including slow sand filters, upward slow sand filters and rapid sand filters [26]. Slow sand filters may effectively remove pathogen from treated water without the need of chemical assistance, whereas upward flow sand filters and rapid sand filters requires the use of flocculant chemicals to perform effectively. Sand filtration is commonly used to reduce BOD_5, phosphorus and suspended solids (SS) in the effluent. BOD and phosphorus are both associated with SS, therefore eliminating SS to very low levels will greatly reduce the BOD_5 and phosphorus. Besides that, filtration process removes a large number of particles from wastewater, thus, allowing proper disinfection and esthetic acceptance of reclaimed water for useful purposes. The effluent quality by using sand filtration system effectively improve the removal performance in terms of solids and organic [27] and fulfill the criteria from the Department of Environment (DOE) Standard of Standard A and B.

Coagulation refers to the process by which colloidal particles and extremely fine solid solids found in wastewater combined into bigger agglomerates that can be separated via sedimentation, flocculation, centrifugation, filtration, or other separation procedures [28]. The aim of coagulation process is to allow the particles to bind together. Coagulation process is commonly achieved by adding positively charged chemicals such as alum, $FeCl_3$ and $FeSO_4$ to the wastewater in order to enhance colloid dispersion instability and the agglomeration of the colloidal particles [24]. According to Zaleschi et al. [29], tertiary treatment using chemical coagulation–flocculation is among the favorable treatment processes for the purpose of wastewater reclamation. The effluent quality resulted from this treatment process (as shown in Table 2) do meet with Department of Environment (DOE) Standard of Standard A and B.

2.3. Advanced treatment

Advanced treatment refers to the process that are designed to produce higher quality effluent compare to the normal secondary treatment processes. There are great numbers of advanced treatment processes including activated carbon and advanced oxidation processes.

Activated carbon with grain diameter smaller than 0.074 mm are known as powdered activated carbon (PAC) while granular activated carbon (GAC) refers to activated carbon that have particle diameter larger than 0.1 mm. The preparation of activated carbon usually involves carbonization of raw materials (i.e., fruit stones and peat) and the carbonized product activation [30]. PAC can be applied directly to the activated sludge or solids contact processes and upstream of a filtration step during reclamation. Different regulated synthetic organic substances as well as unregulated trace organic compounds with high and moderate hydrophobicity (i.e., steroid hormones, triclosan, bisphenol-A), are effectively removed by activated carbon [31]. Activated carbon can be used either to treat raw wastewater or treated effluent of the wastewater. Evidence reported that the application of activated carbon is effective on both types of samples. According to Ademiluyi et al. [32], activated carbon are capable in treating polluted industrial wastewater and achieved minimum of Standard B for all stated parameters.

Advanced oxidation processes (AOPs) are groups of oxidative wastewater treatments processes that are utilized to remediate toxic effluents from industrial, hospitals, and

Table 2
Effluent quality of chemical coagulation–flocculation [29]

Parameter	Effluent quality when using alum (mg/L)	Effluent quality when using iron (mg/L)	DOE Standard A:B (mg/L)
Turbidity	<0.5	<0.5	–
SS	4	2	50:100
COD	59	30	120:200
Total nitrogen	8	7	–

others wastewater treatment facilities. Toxic organic molecules (i.e., drugs, pesticides, endocrine disruptors etc.) are successfully transformed into biodegradable substances by using AOPs [33]. It can be used as tertiary treatment after secondary biological treatment of wastewater, or as pre-treatment stage in order to improve the trace organic pollutants' biodegradability [34]. Advanced oxidation generally employs powerful oxidizing agents (i.e., ozone (O_3) or hydrogen peroxide (H_2O_2)), catalysts (iron ions) and irradiation (UV light) separately or with combination under mild conditions such as low pressure and temperature. AOPs can eliminate organic contaminants and in-organic metals in wastewater treatment and are also successful in inactivating the bacteria and viruses present in the contaminated water [35]. AOP treatment are therefore suitable in treating various kind of wastewater.

2.4. Comparative assessments on wastewater treatment technologies

A study evaluated the cost analysis of STPs containing EA, CAS and SBR system [36]. Based on the study, the highest construction cost was indicated by SBR with approximately US$14,000,000 (RM54,859,000) followed by EA and CAS with total cost of about US$13,500,00 (RM52,899,750) and US$12,500,000 (RM48,981,250), respectively. Fig. 1 illustrates that the operation cost of STPs containing SBR is the highest followed by CAS and EA, maintenance cost of STPs is approximately the same for CAS, EA and SBR, material cost of wastewater treatment plant (WWTP) containing EA is the highest followed by SBR and CAS, chemical cost of STPs is low and approximately the same for CAS, EA and SBR, energy cost of STPs containing EA is the highest followed by SBR and CAS, as well as amortization cost of STPs containing SBR is the highest followed by EA and CAS. Moreover, another study also reported on the higher cost per cubic meter of step aeration process ($1.288) compare to conventional activate sludge system ($1.286) [37]. These results indicates that the STPs with CAS process is the most cost effective compared to its modification processes. Table 3 evidenced the estimation of operational expenditure (OPEX) and capital expenditure (CAPEX) for two mega CAS STPs, STP A and STP B located at Malaysia.

Other than that, according to Ko et al. [38], the total CAPEX of sand filtration treatment system with capacity of 3,785 m^3/d was estimated as $1.9 million (about RM7.7 million), accounted as sum of the costs for land acquisition, equipment (e.g., filter), holding tank, installation, sludge thickener, sludge drying bed, and construction. The annual OPEX was estimated as $120,116 (about RM479,274) including maintenance, electrical energy, labour, polymer, and sludge disposal. The present value (PV)-based 20 y maintenance cost is estimated as $878,894 (about RM3.5 million). Tables 4 and 5 show the capital and operational cost analysis of sand filtration treatment system.

For chemical coagulation treatment process, capital costs including upgrades to existing chemical feed systems, piping, valves, and instrumentation and controls while operating and maintenance costs (OPEX) include

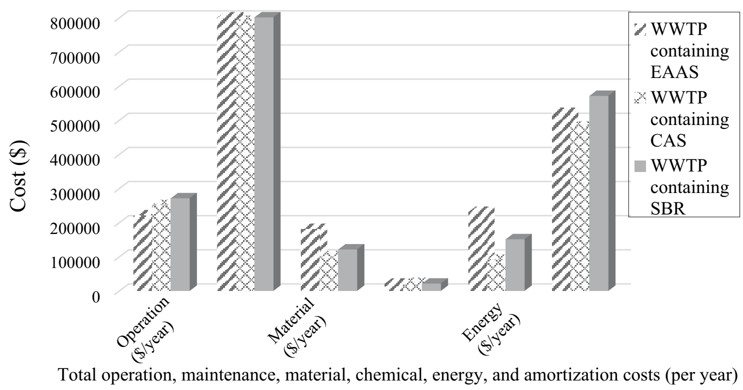

Fig. 1. The total operation, maintenance, material, chemical, energy, and amortization costs (per year) of WWTPs containing EA, CAS, and SBR processes [36].

Table 3
Estimation of OPEX and CAPEX for STP in Malaysia

Type of cost	STP A[a]	STP B[b]
CAPEX		
Engineering design	RM 21,998,366	RM 13,000,000
Manpower	RM 47,516,469	RM 28,080,000
Materials (concrete, bricks, steel, electrical)	RM 51,476,175	RM 30,420,000
Equipment	RM 98,922,645	RM 58,500,000
Total CAPEX	RM 219,913,655	RM 130,000,000
OPEX (Annual)		
Manpower	RM 1,590,000	RM 1,966,000
Materials (chemicals)	RM 1,591,236	RM 1,832,008
Energy	RM 2,452,396	RM 4,275,504
Disposal of sludge	RM 1,270,474	RM 1,234,274
Total OPEX	RM 6,904,607	RM 9,307,686

[a]Capacity plant: 67,124 m^3/d
Capacity plant: 163,969 m^3/d.

power, chemicals, replacement parts and maintenance labor. Table 6 shows the cost function that is proposed by Guo et al. [39] for estimation of capital and annual O&M cost for coagulation and flocculation treatment system. According to Englehardt and Wu [40], the suggested cost for coagulation system for 1.51 m^3/d (400 GPD) was $1,500 (about RM 6,080) for capital cost and $600 (about RM 2,430) for annual O&M cost.

Besides that, a study by Meidl [41] mentioned that the activated carbon treatment system in particular PAC is about 10% less in CAPEX of the conventional activated sludge (CAS) treatment facilities. The estimated cost per cubic meter for the PAC treatment system is $0.98 compared to $1.05 for the CAS treatment system. In addition, the dewatered sludge amount for PAC treatment system is less compare to CAS [41]. According to Foy and Close [42], Burns & McDonnell added PAC to the CAS process at a petrochemical facility to reduce the overall effluent toxicity. After addition of PAC to the CAS process, COD removal, ammonia removal, and toxicity (survival) were 90%, 100%, and 100%, respectively. To avoid settling, material erosion, motor overloads, and line plugging, adding PAC to existing wastewater treatment facilities may requires mechanical improvements beyond the PAC feed system [42].

The cost for AOPs are largely depends on the effluent quality and the aim of the final process. According to some of the studies, it is suggested to work on pilot testing to predict the specific site costs. It was observed that the flow-rate and removal efficiency were the key contributors of the expenses [43,44]. Moreover, it should also be noted that the operating cost for wastewater treatment per cubic meter are slightly different among different countries. For example, the operating cost for wastewater treatment technologies in developing countries are higher compare to developed countries such as United States [45]. The capital costs and operating and management costs increased significantly when removal efficiency improved [46]. According to Kommineni et al. [46], the costs of AOP were grouped into three different categories, operational, capital, and O&M. The total investment costs of the treatment system include its installation. Table 7 summarize on the cost estimation for AOP Unit. Each of the installation costs was computed as part of the capital costs. Valves, Piping, and electrical work are approximately 30%, site work is 10%, engineering is 15% and contractors is 15%

Table 4
Capital cost analysis of sand filtration treatment system [38]

Item	Cost
CAPEX	
Land acquisition, $	29,233
Equipment (e.g., filter), $	896,971
Holding tank, $	30,186
Instalment, $	324,505
Sludge thickener, $	72,461
Sludge drying beds, $	137,676
Total construction cost, $	1,491,032
Engineering and contingency, $	447,310
Total capital cost, $	1,938,342

Table 5
Operational cost analysis of sand filtration treatment system [38]

OPEX (annual)	
Maintenance, $/y	77,534
Electrical energy, $/y	4,935
Labour, $/y	32,050
Polymer, $/y	2,084
Sludge disposal, $/y	3,513
Total operational cost, $/y	120,116

Table 6
Cost function for coagulation and flocculation treatment system (y = cost, x = plant capacity m^3/d) [39]

Wastewater treatment technologies	Capital cost ($)	Annual O&M cost ($)
Coagulation and flocculation	$\log(y) = 0.222 \times (\log(x))^{1.516} + 3.071$	$\log(y) = 0.347 \times (\log(x))^{1.448} + 2.726$

of the equipment costs. Additionally, a contingency of 20% of the total cost was included. The annual capital cost was amortized over a 30 y period at a 7% discount rate. Among all AOP treatment systems, H_2O_2/O_3 and H_2O_2/UV looks to be the two most promising AOP systems, and they are both economically practical [47].

Taking everything into account, Table 8 summarizes on the treatment process based on the effluent quality and cost (OPEX and CAPEX). Based on Table 8 and each of the treatment processes discussed in previous part in terms of effluent quality and cost (OPEX and CAPEX), it can be observed that the estimated cost per population equivalent (PE) of the conventional activated sludge process is the lowest and provided that the treated effluent quality is approximately the same among the secondary treatment process. These results indicate that that the STPs with CAS process is better in terms of cost effectiveness compared to its removal performances among the secondary treatment process. This statement is supported by Arif et al. [48] which reported that the activate sludges system is capable in meeting the effluent quality standard with relatively lower cost. It was observed that the price of inflow per cubic meter of CAS plant is 0.2$ which is lower compare to the alternative treatment technologies investigated such as membrane bioreactor.

For tertiary treatment, the estimated cost for sand filtrations is much lower compared to the chemical coagulation and flocculation while for advanced treatment activated carbon is the better options due to its performance in terms of effluent quality and cost effective. According to Azis et al. [49], sand filtration is widely utilized in the tertiary wastewater treatment due to low operating and capital cost, efficient treatment performance in terms of suspended solids and easy in handling and maintenance. In addition, according to, the CAPEX of the PAC system is 10% less compared to (CAS) treatment system and the combination of PAC with CAS will largely improve the overall removal performance.

Table 7
Cost estimation for AOP unit [46]

Type of cost	Cost (in USD)
Advanced oxidation unit	1,200,000
Piping, valves, electrical (30%)	360,000
Site work (10%)	120,000
Contractor O&P (15%)	252,000
Engineering (15%)	289,800
Contingency (20%)	444,360
Total CAPEX	2,666,160
Amortized capital	214,864
Annual O&M	207,507
Total OPEX (Annual)	422,371
Total cost per 1,000 gallons (about 3.79 m^3) water treated	1.34

3. Conclusions

The recycled waters that fulfill the discharge standards are part of the reliable sources and important criteria in sustainable environmental management. The sewage treatment plant mainly comprised of primary and secondary treatment process and the cost of the treatment process increases from conventional treatment to advanced treatment accordingly. Based on our review, the highest construction cost among secondary treatment was indicated by sequencing batch reactor followed by extended aeration and conventional activated sludge system. Besides that,

Table 8
Summary of the treatment processes based on effluent quality and cost (OPEX and CAPEX)

Treatment process	Effluent quality (mg/L)				Estimated cost/PE[c]	
	BOD_5	COD	SS	AN	OPEX	CAPEX
Conventional activated sludge[b]	13		14		RM15.80	RM340.70
Extended aeration	15		14		RM107.80	RM2479.70
Sequencing batch reactor	18		13		RM117.60	RM2571.60
Sand filtration	<10		<10		RM28.50	RM457.70
Chemical coagulation–flocculation		30	2		RM362.10	RM912.00
Activated carbon	12	156				RM0.90
Advanced oxidation process		77%[a]			RM12.00	RM75.70

[a]Removal percentages;
[b]Data OPEX and CAPEX from Malaysia's STP;
[c]Design flow rate = 0.225 m^3/ca·d.

the total CAPEX for a sand filtration system of 3,785 m^3/d was estimated as \$1.9 million and the annual OPEX was estimated as \$120,116. For chemical coagulation and flocculation process, the estimated capital and annual O&M cost for 1.51 m^3/d coagulation system was \$1,500 and \$600. Lastly, the anticipated cost per cubic meter for PAC treatment system is \$0.98 while the total cost per 1000 gallons water treated by AOP was \$1.34. Therefore, it can be concluded that conventional activated sludge process, sand filtrations and activated carbon process is most feasible in terms of removal performance and cost effectiveness for secondary, tertiary and advanced treatments. Although the comparative assessment between wastewater treatment technologies have been briefly described in this study, intensive studies on other types of wastewater treatment technologies, their effectiveness and specific treatment performances in treating different types of pollutants are still needed in the future in order to increase the public awareness and promotes the usage of recycled wastewater.

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Conflicts of interest

The authors proclaim that there is no known competing financial interests or personal associations that could have seemed to influence the work stated in this paper.

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