IOP Conf. Series: Earth and Environmental Science 1091 (2022) 012056 doi:10.1088/1755-1315/1091/1/012056

Energy efficiency and nutrient removal performance: comparison between several types of activated sludge process

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Abstract. The operation of a wastewater treatment plant entails a huge amount of electricity. The majority of energy inputs are consumed by aeration systems to support biological processes for treated wastewater. Urban wastewater treatment plants are energy-intensive facilities that consume significant amounts of energy. For conventional activated sludge systems, 25% to 60% of the operating costs are associated with energy use. Malaysia's wastewater treatment plants have fallen short in terms of technological advancement in the sewerage industry. The goal of this research is to analyse and make a comparison of the capabilities of the sequencing batch reactor (SBR) and other activated sludge (AS) system treatment plants in Selangor, Malaysia. High energy electricity consumption was an important issue that affected the operational cost and development of wastewater treatment plants (WWTP). The result and discussion for the analysis had been presented into comparison result for each objective of this research studied which was to determine lowest energy efficiency, to assess highest nutrient removal efficiency and compliance rate for each WWTP process plant. This paper presents best practices that can be implemented and adapted by operators in their pursuit of energy and reduce cost or expenses in the sewage treatment plant.

Keywords: Energy efficiency, wastewater treatment plant; nutrient removal; compliance rate; Malaysia.

1. Introduction

Urban wastewater treatment plants (WWTPs) are energy-intensive facilities that consume significant amounts of energy [1]. For conventional WWTPs, 25% to 60% of the operating costs are associated with energy use. Electricity was the main energy source to operate the wastewater plant and to ensure all equipment ran without fail. It has been reported that electric power consumption was 15% - 30% of the total running costs for the larger WWTP compared to 30% - 40% for the smaller WWTP. The Malaysian government makes significant investments to ensure that our drinking water is indeed clean and safe. The wastewater treatment plant (WWTP) was one of the investments because it produces safer treated water from wastewater. Because of the high cost of operation and maintenance, the investment in WWTP was quite high. Sewage treatment plants (STP) in municipalities are energy-intensive facilities that use a lot of power consumption [2]. Energy efficiency has been becoming an issue of global concern. Energy efficiency was introduced and implemented in this study by using an energy performance index (EPI) method. More advanced treatment technologies are required in sewage treatment plants (STP) to improve the removal efficiency of organics and nutrients to meet increasingly stringent discharge regulations.

The energy consumed, largely in the form of electricity, was mainly used for two main functions, which were to provide mechanical equipment (usually powered by pumps and mixers) and to provide oxygenated air (also called aeration). Reports indicate that aeration was a major contributor to energy consumption, estimated at 50% – 75% of total treatment plant energy expenditure. Malaysia is currently lagging in terms of innovations and technologies for mechanizing sewage treatment plants. There was a great deal of old and conventional activated sludge that needed to be properly maintained because of the high operation costs due to industrial tariffs, high electricity usage, and low efficiency of the equipment in the plant. Most importantly was the Indah Water Konsortium (IWK), the nation's largest wastewater treatment operator, which operates all wastewater treatment plants throughout Malaysia except Sabah and Sarawak, spending huge expenses annually on maintenance and operational costs. More than 50% of the annual budget was spent purposely on electricity consumption.

The main objective of wastewater treatment plants (WWTP) is to purify treated water. Because energy cost is not a major concern and a big issue for government officials, contractors, and developers, most wastewater treatment plants in operation today are constructed and built with no regard for energy efficiency criteria in mind. Wastewater treatment plants are energy-intensive, especially in terms of electrical energy demands, which contribute to more than 60% of overall electricity usage [3]. A wastewater treatment plant is a sophisticated system for eliminating contaminants from homes and municipal waste. Biological and chemical techniques were employed in a wastewater treatment facility to remove pollutants before the treated water was discharged into a receiver or bodies of water.

The study looked into and compared the efficiency and treatment capacity of sequencing batch reactors (SBR) and other activated sludge (AS) treatment plants in Selangor, Malaysia. The goal of this research was to compare and find the best energy efficiency using the energy performance index (EPI) for each type of process, the most efficient nutrient removal and compliance rate to meet the requirements of Standard A and Para (1) the Department of Environment (DOE) Malaysia. This study will identify which is the best wastewater treatment process that is more efficient, has high nutrient removal, and high compliance rate for WWTP design consideration. The objectives of the study are:

1) To determine the highest compliance rate of between sequencing batch reactor (SBR) plant and several activated sludge (AS) process of intermittent decanted extended aeration (IDEA) plant and extended aeration (EA) plant.
2) To quantify overall nutrients removal percentage and efficiency of organic load for biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia (NH3N), nitrates (NO3N), oil and grease (O&G), and total suspended solids (TSS) with different type of activated sludge (AS) system.
3) To identify energy efficiency and energy performance index (EPI) between sequencing batch reactor (SBR) plant and other plant types of extended aeration (EA) and intermittent decanted extended aeration (IDEA).

2. Wastewater Treatment Technologies

Wastewater treatment plants (WWTP) are an energy-intensive industry that consume high electricity. The wastewater process includes three main stages; physical treatment is used to remove the suspended solids and other impurities. Around 25% of energy is consumed to drive the influent pumps and aerated grit chamber [3]. Much of the energy used in this stage is for the aeration process. Only a small amount of energy is used for pumping water. About 60-70% of energy is used in biological treatment [4]. The process of aeration, which is the most energy-consuming part of the daily operation of wastewater treatment, uses up to 70% of the energy in the facilities. Sludge conditioning and dewatering processes are also significant energy users in conventional wastewater treatment processes. About 10% of wastewater sector energy is used. Preliminary and primary treatment stages are less energy-intensive than conventional secondary treatment, while tertiary treatment can be energy-intensive as secondary treatment depending on the type and quantity of pollutants being removed and the desired and/or regulated effluent quality. The energy efficiency of the wastewater treatment plant is influenced to a great extent by the wastewater treatment technology, plant type, treatment process design, plant categories, and the sewage inflow and effluent quality. Studies of the main process and equipment that contribute to energy consumption are critical to implementing target strategies for energy reduction plan action. Comparison between SBR and other types of plant & energy consumption is shown in table 1.

Table 1. Technology comparison between SBR and other plant types

Parameter	EA	IDEA	MBR	SBR
BOD, mg/l	<30	<30	<3 - <5	<5
COD, mg/l	<250	<250	<100	<100
TSS, mg/l	<100	<100	<5	<10
Area, Acre	10.9	9.0	5.0	6.3
Power Cost, RM/m3	1.71	1.60	3.0	1.14
Maintenance cost, RM/m3	0.22	0.20	1.1	0.27

*Note: EA – Extended Aeration
IDEA – Intermittent Decanted Extended Aeration
MBR – Membrane Batch Reactor
SBR– Sequential Batch Reactor

The comparison technology shows that the SBR and MBR can remove higher pollution loading than the average treatment plant systems in Malaysia, such as EA and IDEA. The SBR could achieve efficiencies between 90% - 96% for BOD and COD removal, 95% for SS removal, and up to 92% for nutrient removal. More advantages for SBR are less electricity consumption and a small area for constructing the wastewater treatment plant compared to others. The demand for wastewater treatment plants has gradually increased because of urbanization, population growth, and improved living standards in many countries. Wastewater treatment plants (WWTPs) have been designed and operated to reduce the pollution of wastewater and to minimize the adverse impacts on environmental quality and human health [5]. Wastewater treatment plants (WWTP) have substantial environmental impacts during their life cycle due to energy consumption, chemical usage, and gas emissions, as well as sludge generation which requires additional treatment for disposal.

Many technologies have been developed for wastewater treatment plants (such as membrane bioreactor, sequencing batch reactor, and others). The evaluation of technology is important for obtaining better economic efficiency, as well as for reducing the environmental lifetime impacts [7]. Properly treated wastewater can be reused for various purposes to provide ecological benefits, reduce the demand for potable water and augment water supplies [8]. Several environmental and health impacts resulting from insufficient wastewater treatment have been identified in the scientific literature and actions need to be taken to reduce these impacts. These impacts can include negative effects on aquatic life and wildlife populations, oxygen depletion, beach closures and restrictions on recreational water use, restrictions on fish and shellfish harvesting.

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3. Methodology

Not much research was studied and journals were found comparing the energy saving of electricity consumption of the SBR system with other types of wastewater treatment plants in Malaysia. The primary source of energy or power required in wastewater treatment plants (WWTP) was electricity, which accounted for approximately around 25% to 50% of the operating cost of conventional activated sludge (AS) plants. The available data of wastewater characterization from the treatment plant and data about electricity consumption have been analysed into a table set using Microsoft Excel. The first step involved a detailed analysis of the nutrient removal which showed the efficiency of removing biological and chemical microbes from incoming influent to effluent discharge with a suitable treatment process for the wastewater. The result was, later on, it had was analysed and identified as a baseline or parameter set for the upper limit and lowered the limit to maintain suitable microbe of sewage in the wastewater treatment process.

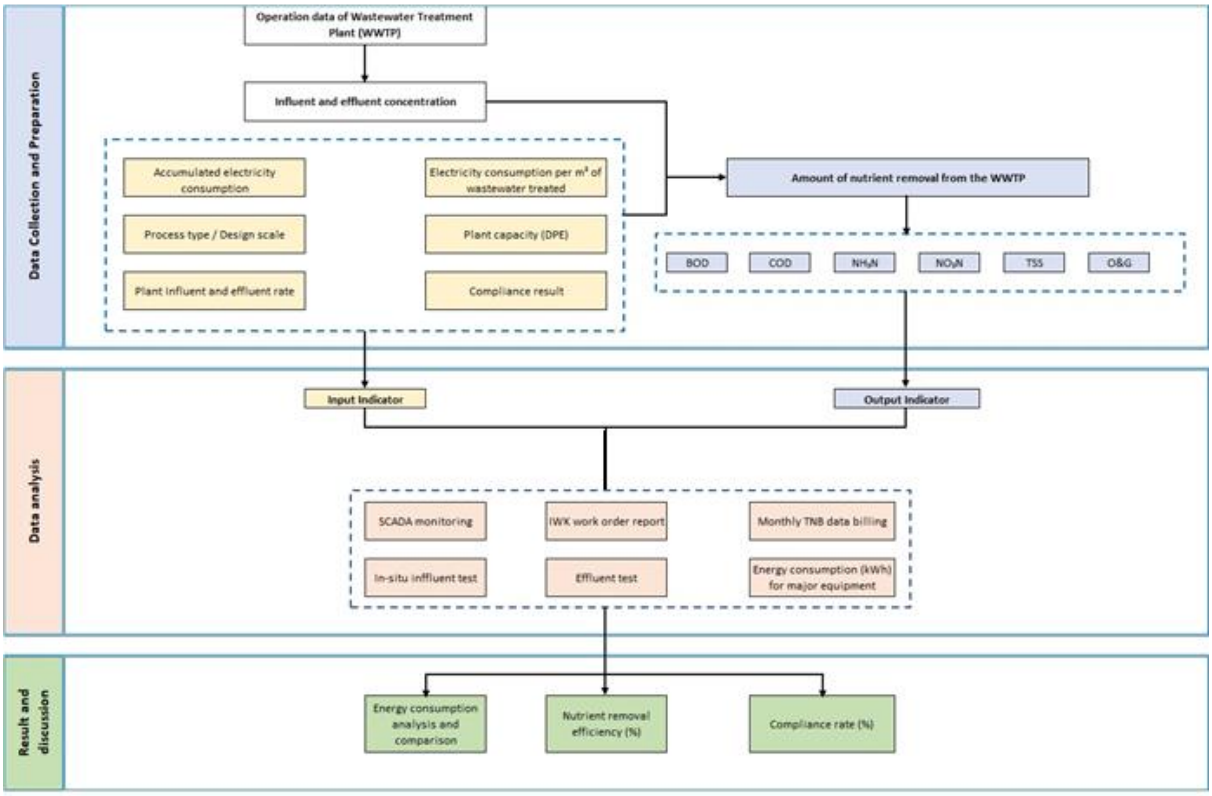

Figure 1. The technical framework of this study

In Figure 1, the evaluation framework is presented. Three steps make up the framework, in which performance data for the three types of wastewater treatment systems (WWTP) for SBR, EA, and IDEA processes were categorized into six inputs. The first step was data collection and preparation, in which the operational data of three types of wastewater treatment system (WWTP) for SBR, EA, and IDEA processes were categorized into six inputs consisting of accumulated electricity consumption data, process plant type, plant influent and effluent rate data, electricity consumption per m³, plant capacity and sludge production data. Meanwhile, six output indicators of biological removal in the wastewater process consist of BOD, COD, NH_3N, NO_3N, TSS, and O&G. Then, the indicators of all wastewater treatment plants (WWTP) were calculated and analyzed with Microsoft excel for comparison results of electricity consumption, nutrient removal efficiency, and sludge production. For the data collection in this research study, there were six inputs that needed analysis. That consisted of SCADA monitoring data logger. The IWK supervisor ordered the report, monthly TNB data billing for electricity usage, in-situ test result for influent sewage, effluent result compliance, and energy consumption (kWh) for major equipment at each plant. Finally, the result and discussion for the analysis are presented in comparison with each objective of this research study, which was to determine energy consumption, to assess nutrient removal efficiency and compliance rate for each WWTP process typed. The duration of this research study would take 2 years and start from January 2019 until December 2020.

3.1. Study area

The sewage treatment plant (STP) in this case study was located on Peninsular Malaysia's west coast. Sequencing batch reactor (SBR), intermittent decanted extended aeration (IDEA), and extended aeration (EA) were chosen for the three-type mechanized wastewater treatment plant (WWTP). All the STP were categorized as Standard ‘A’ and Para (I) under the Environmental Quality (Sewage) Regulation 2009 (EQSR 2009). Effluent from the plant was measured by a flowmeter when discharged into the nearest river. Wastewater treatment typically involves one of several types of processes, known as preliminary treatment, primary treatment, secondary treatment, and tertiary treatment. The wastewater treatment plant that was selected was located in Selangor, Malaysia, and under Indah Water Konsortium Sdn Bhd operation to undergo this research study. Table 2 shows that the capacity loading rate for SBR is 50%, EA is 69%, and IDEA is 53% of the total ultimate plant loading. Detailed description of other plants that were selected for this comparison study as per Table 2 below;

Table 2. Description and Capacity of Sewage Treatment Plant for this case study

Plant Type	**Sequential Batch Reactor (SBR)**	**Extended Aeration (EA)**	**Intermittent Decanted Extended Aeration (IDEA)**
Design Population Equivalent (DPE)	150,000 PE	108,000 PE	134,000 PE
Current Population Equivalent (CPE)	75,000 PE	75,000 PE	70,500 PE
Design treatment capacity (m^3 /day)	16,875.00 m^3 /day	16,875.00 m^3 /day	15,873.75 m^3 /day

* Note: PE = Population Equivalent

4. Result and Discussion

There was a clear relationship between the plant operators in designing wastewater inflow, energy, and nutrient removal efficiency. A sewage treatment facility with a low load rate, defined as the volume of sewage applied to a particular treatment process, would have poor energy performance, and such low-capacity utilization would result in increased energy expenditure. It indicates that equipment and processes are most efficient when working under design flow circumstances, for example, when the wastewater treatment facility is at full capacity. When the load rate reached its optimum value, equipment and process operations were more efficient because process operations were more stable than when the loading rates were reduced. Indeed, the operation of the treatment process shows minimal changes in wastewater volume and pollutant concentrations, and conditions are more favourable for microorganisms and sludge growth.

4.1. Plant Performance and Nutrient Removal Efficiency

To argue objectively about the performance of each process technology, relevant data on plant operations were collected and analysed from January 2019 to December 2020. Table 3 shows the comparison of maximum nutrient removal efficiency (BOD, COD, NH_3N, NO_3N, TSS, and O&G) result that has been collected as the following;

i. With an average efficiency of 97.5%, SBR and IDEA wastewater treatment plants have the highest removal efficiency for BOD and COD.
ii. The SBR wastewater treatment plant has the highest NH_3N removal efficiency with an average efficiency of 94.5 percent, followed by IDEA (86.5%) and EA (82.5%).
iii. SBR treatment plant has the highest removal efficiency for NO_3N with an average efficiency of 98%, followed by EA with 89%, and IDEA with 85.5%.
iv. EA treatment plant has the highest removal efficiency for O&G with an average efficiency of 95.5%, followed by IDEA with 91.5% and SBR with 88%.

Based on the results, the SBR treatment plant had the highest score for nutrient removal of BOD, COD, NH_3N, NO_3N, and TSS compared to other activated sludge systems. EA and IDEA have the highest scores of O&G nutrient removal due to the extra retention time and clarifier in both processes, so both activated sludge systems managed to remove more oil and grease. It can be concluded that the SBR treatment system achieves the highest efficiency in treating the wastewater treatment system in terms of water quality; additionally, the SBR method has the added advantage of simplicity and lower cost when compared to other activated systems, according to the qualitative assessment. Nitrogen removal from wastewater can assist to lessen these impacts. Biological nutrient removal (BNR) is a sludge-based method that involves careful environmental management to promote nitrification, denitrification, and nitrate removal, which results in nutrient removal. The sequencing batch reactor (SBR) system was the best process of nutrient removal in removing the BOD, COD, NH_3N, NO_3N, and TSS with average efficiency from 2019 to 2020, is 97.5%, 91.5%, 94.5%, 98 %, and 96.5% Meanwhile extended aeration process (EA) was the best in removing BOD and O&G with the efficiency is 97% and 95.5%. Intermittent decanted extended aeration (IDEA) was the best in removing BOD, COD, O&G, and TSS with efficiency of 97.5%, 91.5%, 91.5%, and 92%. The result that can be concluded from Table 3 shows that the best treatment plant for nutrient removal efficiency is SBR followed by IDEA and EA system processes.

Table 3. Nutrient removal efficiency from 2019-2020

			Nutrient Removal Efficiency (%)					
Wastewater Treatment Plant type	**DOE Para**	**Years**	**BOD**	**COD**	**NH_3-N**	**NO_3-N**	**O&G**	**TSS**
Sequential Batch Reactor (SBR)	1	2019	98	91	94	98	88	96
		2020	97	92	95	98	88	97
		Avg (%)	97.5	91.5	94.5	98	88	96.5
Extended Aeration (EA)	1	2019	98	91	88	88	96	84
		2020	96	89	77	90	95	86
		Avg (%)	97	90	82.5	89	95.5	85
Intermittent Decanted Extended Aeration (IDEA)	1	2019	97	92	85	85	91	93
		2020	98	91	88	86	92	91
		Avg (%)	97.5	91.5	86.5	85.5	91.5	92

4.2. Compliance Rate Efficiency

As can be seen in Table 4, the main objective of determining the wastewater treatment plant (WWTP) with the highest compliance rate has been achieved. For SBR, from a total sample of 49 in 2019, that plant managed to comply 48 times, with an equivalent to a 98% compliance rate. Meanwhile, in 2020, there were a total of 48 samples being taken and SBR only complied 47 times, which was equivalent to 98% of the compliance rate. This result shows that SBR systems are very efficient in removing nutrients and are the most efficient process system. The total sample for compliance was taken every week (12 Months x 4 weeks = 48 samples) since it was the requirement from the DOE to ensure that the wastewater treatment plant meets the regulations and standards to discharge treated wastewater into the river. For IDEA, from a total sample of 49 in 2019, that plant managed to comply 47 times, with an equivalent to a 96% compliance rate. Meanwhile, in 2020, there is a total of 48 samples sampling have been taken and IDEA only complied 43 times. That was equivalent to 90% of the compliance rate due to the major equipment being broken down and under repair. Lastly for EA, from a total sample of 49 in 2019, that plant managed to comply 45 times, with an equivalent to a 92% compliance rate. Meanwhile, in 2020, there were a total of 50 samples taken and EA only complied 45 times that were equivalent to 90% of the compliance rate due to some major equipment being broken down.

Table 4. Compliance result from 2019-2020

		Compliance Result				
Wastewater Treatment Plant type	**DOE Para**	**Years**	**Total Sample**	**Comply**	**Non-Comply**	**%**
Sequential Batch Reactor (SBR)	1	2019	49	48	1	98
		2020	48	47	1	98
Extended Aeration (EA)	1	2019	49	45	4	92
		2020	50	45	5	90
Intermittent Decanted Extended Aeration (IDEA)	1	2019	49	47	2	96
		2020	48	43	5	90

The best wastewater treatment plant was a sequencing batch reactor (SBR), followed by intermittent decanted extended aeration (IDEA) and finally extended aeration (EA). This was because a technology used in SBR was more efficient in removing high-impact wastes with an average incoming of BOD = 92 mg/l and COD = 198 mg/l. The final discharge effluent for SBR managed to reduce and eliminate the nutrients in BOD = 2 mg/l and COD = 17 mg/l. The main advantages of SBR system type parameters were their flexibility, which allows the working parameters to be adjusted according to various conditions or situations needed. On the other hand, such a plant was very complex and required great knowledge of biological aspects as well as an advanced control system to control the treatment process in efficient work.

4.3. Energy Efficiency and Energy Performance Index (EPI)

The cubic meter of wastewater treated per year was used to calculate the energy performance index (EPI) in this study. EPI was a measure of energy intensity used to gauge the effectiveness of the energy management efforts and can be measured as kWh/m3/year. The disaggregated electrical consumption can be measured or estimated, combining the rated power in kilowatt (kW) and the working hours in a year to provide an estimation of kWh used in each stage per unit of time to calculate the total energy consumption in Equation 1. As such, energy units have been measured in kWh/m3 of treated wastewater per year. All the increasing factors of electricity consumption were due to an increase in water demands which was associated with population growth scenarios in an urban area.

$$\text{Energy Consumption} = \text{Operating Hours Daily (h)} \times \text{Power Rating (kW)} = \text{kWh} \quad (1)$$

$$\text{Energy Performance Index (EPI)} = \frac{\text{Total Energy Consumption (kWh)}}{\text{Total Incoming Influent (Flowrate, m3)}} \ \text{kWh/m3} \quad (2)$$

The energy performance indicator (EPI) calculated in this study is the cubic meter of sewage treated per year (Equation 2). As such, the energy units will be measured in kWh/m3 sewage treated per year. Table 5 show that energy consumption of electricity usage for treatment plants at SBR, EA, and IDEA gradually increased by 6%, 10%, and 23% from the year 2019 to 2020. All the increasing factors of electricity consumption are due to an increase in water demands which is associated with population growth scenarios in an urban area. Total incoming influent flow shows each wastewater treatment received flow increasing which is around 8% for SBR, 13% for EA, and 1% for IDEA from the previous year in 2019 compare to the year 2020.

Table 5. Summary of Energy Performance Index from 2019-2020

Wastewater Treatment Plant type	Years	Energy Consumption (kWh/year)	Flow Rate, Flowmeter (m^3)	Energy Performance Index, EPI (kWh/m^3)
Sequential Batch Reactor (SBR)	2019	1,810,204.00	6,469,959.44	0.28
	2020	1,916,385.00	7,060,808.00	0.27
Extended Aeration (EA)	2019	3,030,778.00	5,184,084.00	0.58
	2020	3,382,053.00	5,933,426.32	0.57
Intermittent Decanted Extended Aeration (IDEA)	2019	1,221,859.00	1,323,925.00	0.92
	2020	1,577,482.00	1,340,859.70	0.85

The benchmark for the energy performance indicator (EPI) will be around 0.2 kWh/m^3 – 0.8 kWh/m^3 for large wastewater treatment plants because the organic pollution load correlates best with energy consumption and also ensures a better comparison between different plants. Factors that influence the energy consumption-total influent flow rate-related energy performance index are known to include catchment area of wastewater treatment plant, treatment plant system type, type of customer service, and operational efficiency. Table 5 shows that the treatment plant SBR system was the highest for energy efficiency with energy performance index. EPI value was 0. 27 kWh/m^3 in the year 2020 with 96% energy efficiency compared with 2019. The second highest in the EA system with 0.57 kWh/m^3 with 98% energy efficiency from 2019 and the lowest energy efficiency for EPI result was the IDEA system with 0. 85 kWh/m^3 with 92% energy efficiency compared with 2019. EPI for 2020, all treatment plants have shown increases in terms of energy efficiency when each plant set the benchmarking to optimum electricity usage.

Other than that, it also shows that the EA plant has high energy consumption with a total average of 3,206,415.50 kWh/year with around a 10% increase from 2019. Followed by SBR and IDEA with each plant's energy consumption around 6% and a 23 % increase from the previous year in 2019. The annual flow was significant because it had the potential to influence the performance of the plant through economies of scale. Furthermore, influent characteristics and pollutant concentrations are regarded as important factors for energy consumption since they influence the treatment process and aeration needs. Table 5 also shows the Energy Performance Index (EPI) scores. The SBR system showed the lowest score of 0.28 kWh/m^3 in 2019 and it was reduced to 0.27 kWh/m^3 in 2020, which shows in terms of energy efficiency, consistency is important. In other words, in terms of energy efficiency, both wastewater treatment plants were comparable. In contrast, the IDEA plant presented the highest score of 0.92 kWh/m³ in 2019 and reduced to 0.85 kWh/m³ in 2020. It shows the inconsistency in the energy efficiency values.

5. Conclusion

This study was successful in comparing the energy efficiency, nutrient removal efficiency, and compliance rate of several activated sludges (AS) systems from three different wastewater treatment plant types (SBR, EA, and IDEA) in Selangor, Malaysia. The conclusion of the study was summarized as follows;

1) The sequencing batch reactor (SBR) plant performed the highest compliance rate based on the regulatory requirements of Environmental Quality (Sewage) Regulation 2009 (EQSR, 2009) compared to others plant types.
2) The sequencing batch reactor (SBR) plant achieved the highest percentage in overall nutrient removal percentage and efficiency of organic load for biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia (NH3N), oil and grease (O&G), and total suspended solids (TSS) with a different type of activated sludge (AS) system.
3) Based on the energy performed index (EPI) calculated, the results also show that sequencing batch reactor (SBR) plants are the most energy-efficient system.

Acknowledgments

The authors have gratefully acknowledged the support from Indah Water Konsortium Sdn Bhd and Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Kuala Lumpur for the cooperation, support, and contribution to the data collection of this study.

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References

[1] Danièle Mousel, Laurence Palmowski and Johannes Pinnekamp. (2017). Energy demand for elimination of organic micropollutants in municipal wastewater treatment plants. *Science of The Total Environment*, **575** 1139-1149.

[2] Guo Z, Sun Y, Pan SY, Chiang PC. (2019). Integration of Green Energy and Advanced Energy Efficient Technologies for Municipal Wastewater Treatment Plants. *Int J Environ Res Public Health*, **16**(7) 1282.

[3] Indah Water Konsortium Sdn Bhd. (2021). The evolution of sewage treatment in Malaysia. *Indah Water Website*.102.

[4] K. Smith and S. M. Liu. (2017). Energy for conventional water supply and wastewater treatment in urban China. *Global Challenges*, **1** 1–6.

[5] T. Xie and C. W. Wang. (2012). Energy consumption in wastewater treatment plants in China.*World Congress on Water, Climate, and Energy*, **34** 1–6.

[6] Wang, H.T, Yang, Y, Keller, A.A, Li, X, Feng, S, Dong, Y.N and Li. (2016) Comparative analysis of energy intensity and carbon emissions in wastewater treatment in USA, Germany, China and South Africa. *Appl. Energy*, **184** 873–881.

[7] Indah Water Konsortium Sdn Bhd. (2019). Sustainability report 2019/2020. *Indah Water Website*, 63.

[8] Al-Shididi, S. Henze, Mogens and Ujang, Z. (2003). Feasibility study of sequencing batch reactor system for upgrading wastewater treatment in Malaysia. *Water science and technology: a journal of the International Association on Water Pollution Research*, **48** 327-35.

[9] LI. Corominas, J. Foley, J.S. Guest, A. Hospido, H.F. Larsen, S. Morera and A. Shaw. (2013). Life cycle assessment applied to wastewater treatment State of the art. *Water Research*, **47** 5480-5492.

[10] Weiwei Mo and Qiong Zhang. (2013). Energy–nutrients–water nexus: Integrated resource recovery in municipal wastewater treatment plants. *Journal of Environmental Management*, **127** 255-267.

[11] L. Luo, M. Dzakpasu, B. Yang, W. Zhang, Y. Yang, X.C. Wang. (2019). A novel index of total oxygen demand for the comprehensive evaluation of energy consumption for urban wastewater treatment. *Appl. Energy*, **236** 253-261.

[12] P. Foladori, M. Vaccari, F. Vitali. (2015). Energy audit in small wastewater treatment plants: methodology, energy consumption indicators, and lessons learned. *Water Sci. Technol*. **72** 1007-1015.

[13] Asano, T., Burton, F., & Leverenz, H. (2007). Water reuse: issues, technologies, and applications. *McGraw-Hill Education*.

[14] Robert L. Irvine, Lloyd H. Ketchum Jr. & Takashi Asano. (1989). Sequencing batch reactors for biological wastewater treatment. *Critical Reviews in Environmental Control*, 255-294.

[15] Uzma Showkat, Ishtiyaq Ahmed Najar. (2018). Study on the efficiency of sequential batch reactor (SBR)-based sewage treatment plant. *Applied Water Science*, **9**.