

PERFORMANCE ANALYSIS OF ADVANCED ANAEROBIC-ANOXIC-OXIC (AAO) REACTOR FOR NUTRIENT REMOVAL IN SEWAGE

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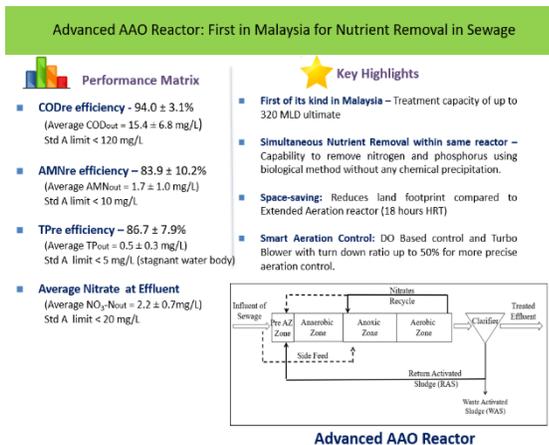
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Graphical abstract



Abstract

Sewage contains significant levels of nutrients, including nitrogen and phosphorus, which can severely harm aquatic ecosystems when discharged untreated. Insufficient removal of these nutrients before discharge may lead to eutrophication that will result detrimental ecological effects to the receiving water bodies. This study investigated the performance of advanced Anaerobic-Anoxic-Oxic (AAO) reactors in a full-scale application in an existing sewage treatment plant (STP) located in Kuala Lumpur where this is the first of its kind operating in Malaysia. This plant utilizes biological treatment method for nitrogen and phosphorus removal without relying on chemical precipitation that will increase the overall operation expenditure of the plant operator. Over 26 weeks, the study evaluated the plant's performance with actual sewage inflows entering the plant with an average treatment capacity of 170 million liters per day (MLD). The findings revealed removal efficiencies of 94.0% for chemical oxygen demand (COD), while nutrient removal efficiencies for Ammoniacal Nitrogen (AMN) and Total Phosphorus (TP) reached 83.9% and 86.7% respectively. The effluent concentrations for AMN, Nitrate Nitrogen (NO₃-N) and TP averaged 1.7 ± 0.1 mg/L, 2.2 ± 0.7 mg/L and 0.5 ± 0.3 mg/L respectively. These results demonstrate that the advanced AAO reactor complies with Standard A effluent discharge limits for COD, NO₃-N and AMN, while achieving a TP effluent concentration below 5 mg/L.

Keywords: Advanced AAO, A2O, Biological Phosphorus Removal, Nutrient Removal

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1.0 INTRODUCTION

Water is a vital resource for sustaining life and maintaining biodiversity on Earth. It fulfills numerous daily needs within communities. However, once utilized, water transforms into wastewater or sewage which often carry contaminants that make it unsuitable for reuse without proper treatment. For example, sewage contains organic matter and nutrients such as nitrogen and phosphorus, which can harm aquatic plants, along with potentially toxic compounds that may have mutagenic or carcinogenic effects [1].

In Malaysia, STPs are required to comply with effluent quality standards, either Standard A or Standard B, depending on the

discharge criteria during the planning submission to certifying agency. The key parameters monitored in a STP include 5-day Biological Oxygen Demand (BOD₅), Total Suspended Solids (TSS), COD, Oil & Grease (O&G), AMN and NO₃-N. The effluent discharge limit for Total Phosphorus (TP) is determined by the nature of the receiving water body, whether it is a river/stream or a stagnant water body. STPs constructed in Malaysia must either follow pre-approved guidelines for design or adopt treatment processes listed in the Malaysian Sewerage Industry Guideline (MSIG) Volume IV. Commonly used treatment methods include Extended Aeration Activated Sludge (EAAS), Sequencing Batch Reactor (SBR) and Conventional Activated Sludge (CAS), which are among the most frequently

implemented sewage treatment technologies in Malaysia [2]. The distribution of sewage treatment technologies currently implemented in Malaysia is illustrated in Figure 1.

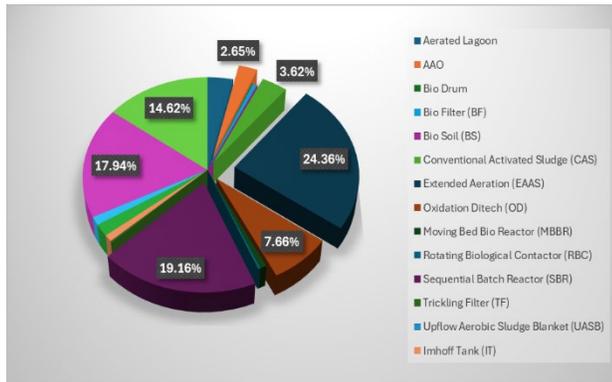


Figure 1 Distribution of Sewage Treatment Technologies in Use in Malaysia in Percentage [3]

The pie chart illustrates the distribution of various sewage treatment methods utilized in Malaysia in percentage of total population equivalent. For suspended growth treatment categories, more than 50% of the STPs employ technologies such as Conventional Activated Sludge (6.28%), Oxidation Ditch (7.66%), Extended Aeration (24.36%), and Sequencing Batch Reactor (19.16%), among others [3]. However, most of the adopted processes are primarily capable of TN removal and are not designed for TP removal. Additionally, STPs classified under Paragraph 2 and Paragraph 3 under EQA 1974 effluent quality (sewage) regulation 2009, allowed higher discharge limits for AMN into receiving water bodies. Under Paragraph 2, STP approved before 1999 only regulates BOD₅, COD, TSS, O&G and AMN with allowable AMN levels varies from 60 to 100 mg/L depending on the type of treatment process. For Paragraph 3 regulates STP approved after January 1999, which has stricter requirements on BOD₅ COD and TSS where AMN limit was also reduce to 50 mg/L [4].

The discharge of excessive nutrients is a significant contributor to environmental issues, such as eutrophication. Although phosphorus is an essential nutrient for microbial growth, its surplus in water bodies can accelerate the eutrophication process [5]. To mitigate this problem, regulations on nutrient discharges are becoming increasingly stringent worldwide [6]. Biological Nutrient Removal (BNR) processes have gained global recognition as an effective solution for simultaneously removing nitrogen and phosphorus. These processes offer substantial economic advantages over chemical treatment methods, making them a preferred choice for sustainable wastewater management [7].

The AAO process is a well-established biological treatment method for sewage worldwide. It integrates nitrification, denitrification and phosphorus removal, making it a widely adopted technology in STPs [8]. Its simplicity and effectiveness in simultaneously removing nitrogen, phosphorus and organic compounds have made the AAO process a popular choice for many STPs [9]. The AAO process has served as the backbone of Biological Nutrient Removal (BNR) in STPs, particularly for TN and TP removal. Under anaerobic conditions, polyphosphate-accumulating organisms (PAOs) release phosphorus, enabling its

uptake during subsequent aerobic phases [10]. This process synchronizes the removal of organic carbon, nitrogen and phosphorus, making it highly effective in addressing eutrophication and improving effluent quality [11].

Although the AAO process performs well in treating municipal sewage, certain limitations remain that hinder its ability to maximize pollutant removal efficiency. A common issue is the low carbon-to-nitrogen (C/N) ratio in influent wastewater, which can hinder denitrification. This emphasizes the need for optimized influent carbon management or the addition of external carbon sources [12]. Nitrification-denitrification processes, under low dissolved oxygen (DO) conditions, have been shown to enhance nitrogen removal efficiency while reducing aeration costs [11]. However, the aerobic zone's high aeration requirements contribute significantly to energy consumption. Balancing the DO levels to optimize nitrification while maintaining energy efficiency remains a critical challenge [10]. Furthermore, low temperatures can inhibit the activity of nitrifying bacteria, thereby affecting nitrogen removal efficiency. Innovative configurations, such as incorporating biofilm carriers, can stabilize nitrification performance under such conditions [10]. Another critical factor influencing the AAO process is hydraulic retention time (HRT) and the recycling ratio. Studies on three-stage AAO continuous systems have shown that increasing the recycling ratio to the anoxic zone significantly enhances nitrogen removal efficiency [13].

To address these limitations, studies have demonstrated that hybrid systems combining the AAO process with other technologies significantly enhance its performance. For instance, integrating the Moving Bed Biofilm Reactor (MBBR) with AAO improves nitrification efficiency by increasing the microbial surface area for biofilm development, thereby supporting simultaneous nitrification and denitrification [14]. The step-feed approach, which redistributes influent sewage across multiple anoxic and aerobic zones, has also proven effective in optimizing carbon utilization and nutrient removal efficiency. This configuration is particularly beneficial for reducing operational costs while meeting stringent discharge standards [15]. Additionally, hybrid systems that combine Enhanced Biological Phosphorus Removal (EBPR) with AAO have achieved phosphorus removal rates as high as 98%, outperforming conventional methods by increasing phosphorus removal efficiency under variable operating conditions [16].

However, while conventional AAO processes are generally effective, they are limited in their ability to handle high influent variability and comply with increasingly stringent discharge standards. This limitation underscores the importance of modified configurations, such as hybrid AAO systems, to address these challenges effectively [17]. Vo *et al.* introduced an extended AAO model (AAO/O) that incorporates an additional oxic zone to increase HRT and improve nutrient removal. This configuration achieved stable removal efficiencies of 93.6% for TN and 91.9% for TP after 60 days of operation [18]. Similarly, Zhou *et al.* explored a modified configuration known as the Reversed Anoxic-Anaerobic-Oxic (RAAO) process. This variation places the anoxic stage before the anaerobic stage and demonstrated several advantages, including enhanced nitrogen removal through pre-anoxic denitrification and improved phosphorus removal efficiency via sequential anaerobic and aerobic zones [19].

The advanced AAO reactor was developed to address the limitations of conventional systems, and it represents the first

full-scale implementation of this technology in Malaysia's sewerage industry. Given the unique characteristics of Malaysian sewage, there is a pressing need to evaluate the performance of this advanced sewage treatment system.

The advanced AAO reactor consists of four major zones: the Pre-Anoxic Zone, the Anaerobic Zone, the Anoxic Zone and finally, the Aerobic Zone. Each zone is specifically designed to create unique conditions that facilitate three critical biological processes: TN removal, TP removal and the degradation of organic matter like BOD and COD. This configuration enables a comprehensive treatment process while relying on simple operations and minimal structural complexity. Figure 2 illustrates the typical layout of the advanced AAO reactor as proposed for this study.

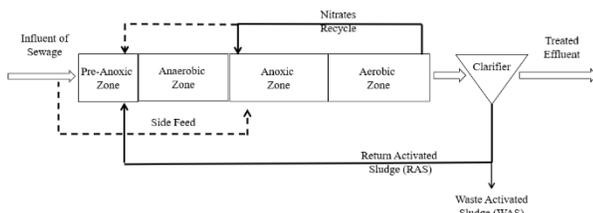


Figure 2 Typical Configuration of Advanced AAO Reactor

The pre-treated sewage flows into the first compartment, known as the pre-anoxic zone, which serves as an anoxic selector. This zone inhibits the growth of filamentous bacteria and prevents sludge bulking. Within this compartment, return activated sludge (RAS) is mixed with influent sewage, enabling microorganisms to utilize nitrites within the RAS, thereby enhancing the performance of the subsequent anaerobic zone.

In the anaerobic zone, microorganisms degrade polyphosphates stored within their cells and assimilate organic compounds, such as fatty acids, from the sewage. This activity results in the release of phosphorus under anaerobic conditions, with subsequent phosphorus absorption occurring during the aerobic phase [20]. In the anoxic zone, microorganisms utilize organic carbon as an electron donor and nitrate as an electron acceptor under low DO conditions. For the advanced AAO reactor, there is a side feed capability where 0% to 25% of the influent BOD₅ (sewage) can be diverted from the inlet to the anoxic zone compartment. This serves as a carbon source supply to the anoxic zone to enhance the denitrification process. This process produces and releases nitrogen gas, contributing to nitrogen removal [8]. In the aerobic zone, organic matter, including soluble BOD₅ and COD, is removed through the absorption and metabolism of microorganisms. Simultaneously, nitrification occurs, converting AMN to nitrate, further contributing to nitrogen removal [21].

This study introduces an advanced AAO reactor designed to enhance sewage treatment efficiency, focusing on the effective removal of nitrogen and phosphorus in municipal sewage. The development of this improved process addresses the limitations of existing STPs that rely on conventional technologies, such as oxidation ponds or aerated lagoons. These conventional systems were designed primarily for organic matter removal and did not prioritize nutrient removal, resulting in higher nutrient discharge levels. Consequently, they fall short in meeting the pressing environmental need to reduce nutrient loading from the sewage sector into receiving water bodies.

2.0 METHODOLOGY

The advanced AAO reactor was implemented at a STP located in Kuala Lumpur, marking the first application of this BNR process in Malaysia for simultaneously removing nitrogen and phosphorus. During the study, the plant was operating with an average hydraulic sewage inflow of 170.0 MLD, maintaining compliance with effluent discharge standards set at Standard A. The key operational parameters applied during the study period are summarized in Table 1.

Table 1 Operation parameter of the Advanced AAO reactor

Parameter	Operation Values
Nitrate Recycle Ratio*	100% – 200% of Q _{in}
Return Activated Sludge Ratio	50% – 100% of Q _{in}
Step Feed Ratio*	0% – 25% of Q _{in}
DO level	1.0 – 2.0 mg/L
pH	6 – 9
Temperature	25 – 30°C
ORP for Anoxic Zone	+50 mV – -150mV
ORP for Anaerobic Zone	-100 mV – -250mV

*Actual setting of the operation parameters based on the actual denitrification at the effluent and maintaining the ORP values within the range.

Raw sewage was pumped from the inlet pumping station and underwent pre-treatment, including fine screening, grit removal and grease separation, before entering the advanced AAO reactor. These pre-treatment steps ensured the removal of large solids and non-biodegradable materials, enhancing the reactor's operational efficiency. The range of influent sewage characteristics observed during the study is summarized in Table 2.

Table 2 Influent sewage characteristics after coarse screening

Parameter	Unit	Influent Concentration Range**	Influent Design Concentration*
COD	mg/L	108.0 – 491.0	500
AMN	mg/L	2.1 – 25.9	30
TP	mg/L	1.1 – 9.3	10
TN	mg/L	7.8 – 30.4	50

*Reference to MSIG influent design criteria [2]

**Influent concentration was recorded upstream of secondary fine screening, grit, and grease removal chambers to represent raw sewage characteristics before further pre-treatment

The influent concentration range in Table 2 represents values measured after coarse screening but before fine screening, grit removal, and grease separation. The actual influent concentrations entering the advanced AAO reactor may be slightly lower because of solids and COD levels after secondary fine screening, grit and grease removal. The sewage characteristics were analyzed based on weekly average samples collected from the influent sampling point. Both influent and effluent sewage characteristics of the advanced AAO reactor were evaluated using key parameters, including COD, AMN, NO₃-N and TP. The influent COD/TN ratio was 14.8 ± 4.2 which

exceeds a minimum ratio of 6.0 to 1.0 for biological denitrification process. The study was conducted over a 26-week period to monitor the influent sewage conditions and assess the quality of the treated effluent. The analytical methods used for influent and effluent sampling are summarized in Table 3.

Table 3 Analytical method for influent and effluent sampling

Parameter	Standard Method
COD	Reactor Digestion Method of HACH 8000
AMN	Salicylate Method of HACH 8155
NO ₃ -N	Cadmium Reduction Method HACH Method 8039
TP	Acid Hydrolysis Method of HACH 8180
TN (influent)	Persulfate Digestion Method of HACH 10071

Pollutant removal efficiency (P_{RE}) is the key parameter used to assess the performance of the advanced AAO reactor. The calculation provides a quantitative measure of the advanced AAO reactor's ability to reduce pollutant concentrations from influent and effluent. The formula used for calculating P_{RE} is as follows:

$$P_{re} = [(C_{in} - C_{eff}) / C_{in}] \times 100 \quad (1)$$

where:

- P_{RE} = Pollutant Removal Efficiency
- C_{in} = Influent Sample Concentration in mg/L
- C_{eff} = Effluent Sample Concentration in mg/L

This formula evaluates the effectiveness of the advanced AAO reactor in reducing pollutant concentrations. A higher P_{RE} value indicates better performance in removing contaminants from the sewage. The MLSS concentration of the reactor are operated at average 3,500 mg/L and by maintaining the MLSS concentration the waste sludge is being calculate where it is drawn out based on 16 hours daily operation by controlling the variable speed of the waste pump.

3.0 RESULTS AND DISCUSSION

In this study, actual sewage was used as the influent for the advanced AAO reactor. Before entering the reactor, the sewage underwent pre-treatment to ensure its suitability for treatment. The influent sewage characteristics provided a baseline for evaluating the reactor's performance. The evaluation of the advanced AAO reactor was conducted by monitoring the concentrations of key parameters. The average influent sewage conditions and the reactor's treatment efficiency are summarized in Table 4.

Table 4 Influent and treated effluent condition and removal rates

Parameter	Unit	COD	AMN	NO ₃ -N	TP
Average inlet	mg/L	271.2 ± 67.1	11.2 ± 4.9		3.6 ± 1.3
Average outlet	mg/L	15.4 ± 6.8	1.7 ± 1.0	2.2 ± 0.7	0.5 ± 0.3
Average removal efficiency	%	94.0 ± 3.1	83.9 ± 10.2		86.7 ± 7.9

The advanced AAO reactor demonstrated high treatment efficiency, particularly for COD, AMN and TP, underscoring its effectiveness in meeting Standard A effluent discharge requirements. The average influent COD concentration was recorded at 271.2 ± 67.1 mg/L, which was reduced to an average effluent concentration of 15.4 ± 6.8 mg/L, achieving a removal efficiency of 94.0 ± 3.1%. This significant reduction reflects the advanced AAO reactor's robust capability to degrade organic matter, consistent with findings by Fang *et al.*, who highlighted the effectiveness of AAO systems in organic removal [9]. For nutrient removal, the influent AMN concentration averaged 11.2 ± 4.9 mg/L, with the effluent reduced to 1.7 ± 1.0 mg/L, resulting in a removal efficiency of 83.9 ± 10.2%. This performance underscores the effectiveness of the pre-anoxic and anoxic zones in facilitating denitrification, aligning with the findings of Lei *et al.*, who emphasized the critical role of denitrifying microorganisms in AAO processes [8]. Effluent NO₃-N concentrations averaged 2.2 ± 0.7 mg/L, well below the Standard A limit of 20 mg/L. This demonstrates the reactor's ability to effectively reduce nitrate levels, further supporting the importance of optimizing the anoxic zone for enhanced denitrification, as highlighted by Xiaolian *et al.* [6]. The influent TN measured for the influent ranged from 7.8 to 30.4 mg/L with an average concentration of 19.0 ± 4.6 mg/L.

For TP removal, the advanced AAO reactor demonstrated strong performance, with influent concentrations of 3.6 ± 1.3 mg/L reduced to effluent concentrations of 0.5 ± 0.3 mg/L, achieving a removal efficiency of 86.7 ± 7.9%. The high efficiency can be attributed to the role of the anaerobic zone in facilitating phosphorus release, followed by its subsequent uptake in the aerobic zone. This is consistent with findings by Eghombi *et al.*, who emphasized the critical role of PAOs in phosphorus removal [20].

The advanced AAO reactor consistently met the effluent Standard A requirements, as outlined in the MSIG requirements [2]. Effluent concentrations for COD, AMN, NO₃-N and TP were well below regulatory limits, ensuring minimal environmental impact on receiving water bodies. Moreover, the advanced AAO reactor's performance highlights its significant potential to mitigate eutrophication risks caused by excessive nutrient discharge, as described by Izadi *et al.* [5]. The overall removal efficiencies of TP, COD and AMN achieved by the advanced AAO reactor are presented in Figure 3.

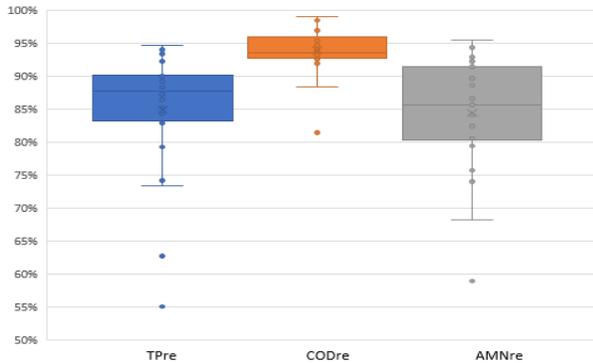


Figure 3 Removal efficiencies of TPre, CODre and AMNre for the Advanced AAO Reactor

This figure 3 illustrates the removal efficiencies of TP, COD and AMN achieved by the advanced AAO reactor. For TP, the average removal efficiency was approximately 86.7%, with most data points clustered above 80%, indicating consistent phosphorus removal. A few outliers below 65% suggest occasional performance fluctuations, likely caused by variations in influent characteristics and hydraulic loading. The consistent TP removal efficiency aligns with findings by Eghombi *et al.*, who highlighted the critical role of PAOs in phosphorus release and uptake cycles [20]. Vo *et al.* demonstrated the efficacy of aerobic and anoxic adjustments in augmenting biological phosphorus removal (BPR) using their AAO-O system, which obtained 91.9% TP removal efficiency. Similarly, in an AAO-MBR system, Eghombi *et al.* found $91.9 \pm 3.5\%$ TP removal, emphasizing the contribution of membrane bioreactor integration to enhanced phosphorus removal efficacy. Furthermore, in a traditional A2O system, Lei *et al.* reported 62.53% TP removal, suggesting that ordinary AAO-based procedures would be less successful in removing phosphorus in the absence of additional process modifications [8, 18, 20].

For COD, the removal efficiencies demonstrated the highest consistency, with a median near 94% and minimal variability. This reflects the robust performance of the aerobic zone in degrading organic matter, even under fluctuating influent conditions. The stability of COD removal efficiency is consistent with observations by Fang *et al.*, who reported similar reliability in organic degradation within AAO systems under variable influent conditions [9]. In an A1/A2/O-MBR system, Zhao *et al.* reported 93.9–97.5% COD elimination, illustrating the effect of membrane bioreactor integration on organic decomposition [17]. In a similar, Izadi *et al.* demonstrated the importance of improved biological phosphorus removal methods in enhancing organic matter breakdown by achieving 90–95% COD elimination in an EBPR process [5]. In contrast, Eghombi *et al.* and Vo *et al.* reported lower COD removal efficiencies of 71.8% in AAO-MBR and AAO/O configurations, respectively, which may be attributed to process limitations or insufficient carbon availability [18, 20]. A study by Lei *et al.* found 88.75% COD removal in a conventional A2O process, which, while effective, did not reach the performance levels observed in the optimized AAO system [8].

For AMN, the removal efficiency showed a high median performance of around 84%, with slightly more variability compared to COD. The wider interquartile range and a few outliers suggest occasional challenges in denitrification during the study period. These challenges are consistent with findings

by Lei *et al.*, who emphasized the influence of carbon source availability and anoxic zone optimization on denitrification efficiency. The study also observed 80.12% AMN removal in a conventional A2O process, which is lower compared with the performance of this study [8]. In contrast, Zeng *et al.* reported 95% AMN removal in an A2O system, highlighting the effectiveness of traditional nitrification-denitrification pathways in optimized systems [11]. However, Zhao *et al.* found a wider range of 71.1–85.3% AMN removal in an A1/A2/O-MBR system, suggesting that membrane bioreactors can influence AMN reduction efficiency based on operating conditions [17]. The high AMN removal efficiency in the advanced AAO system can be attributed to optimized nitrification-denitrification conditions, including DO and ORP control, nitrate recirculation strategies which improved process stability. Compared to conventional AAO and A2O systems, this study demonstrates competitive nitrogen removal efficiency, reinforcing the effectiveness of pre-anoxic zones and internal carbon utilization strategies in enhancing AMN reduction.

The overall performance of the advanced AAO reactor, achieving consistent removal efficiencies for TP, COD and AMN, corroborates findings the literature review who highlighted the adaptability of AAO processes to fluctuating influent characteristics [11]. The variation in influent and effluent COD concentrations, together with the corresponding removal efficiency, is presented in Figure 4.

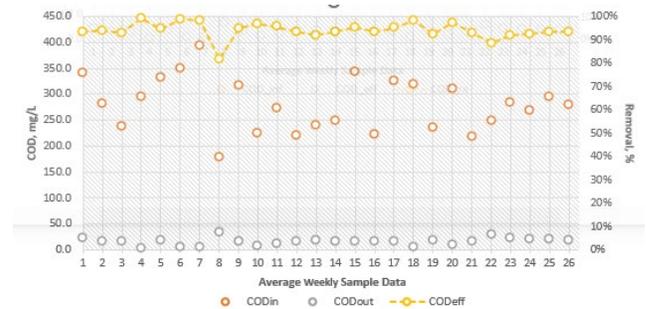


Figure 4 Difference in COD concentration and removal efficiency for influent and effluent weekly average data

The influent average weekly COD concentrations remained relatively stable throughout the monitoring period, averaging 271.6 mg/L, with minor fluctuations attributed to variations in influent sewage characteristics. The effluent weekly average COD concentrations demonstrated consistent reductions, averaging below 20 mg/L, highlighting the advanced AAO reactor's robust capacity for organic matter removal and the oxidation of organic pollutants. The COD removal efficiency curve showed consistently high performance, with an average efficiency exceeding 90% throughout the study period. This exceptional performance aligns with findings from previous studies. Fang *et al.* reported similar efficiencies in AAO systems, attributing these results to the effective synergy between the anaerobic, anoxic, and aerobic zones, which work collectively to break complex organics and enhance microbial activity [9]. Chen *et al.* reported that an A2/O-BAF system consistently maintained effluent COD levels below 50 mg/L, aligning with regulatory discharge limits [7]. Similarly, Zhao *et al.* observed effluent COD concentrations below 20 mg/L in an A1/A2/O-MBR system, demonstrating the effectiveness of membrane bioreactors in COD reduction [17]. Lei *et al.* found that a conventional A2O

process achieved effluent COD levels of approximately 30 mg/L, indicating efficient but slightly lower organic matter removal compared to advanced AAO reactor [8]. On the other hand, Vo *et al.* and Eghombi *et al.* observed higher effluent COD concentrations (~50 mg/L) in AAO-MBR and AAO/O systems, suggesting potential limitations in carbon degradation efficiency due to operational variations [18, 20].

The findings validate the robustness of the advanced AAO system in maintaining stable COD removal performance, even under varying influent conditions. Additionally, Zeng *et al.* highlighted that stable COD removal efficiency is an advantage of the AAO systems, even under varying influent conditions [11].

The variation of influent and effluent AMN concentrations, together with removal efficiency, is shown in Figure 5.

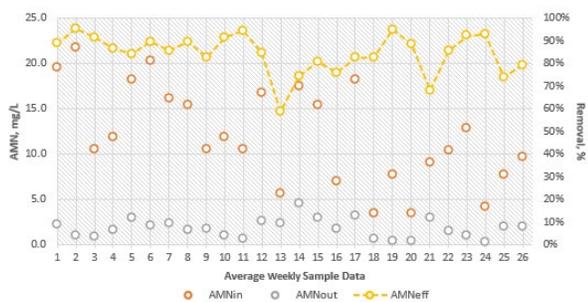


Figure 5 Difference in AMN concentration and removal efficiency for influent and effluent weekly average data

The average weekly influent AMN concentrations ranged from 3.5 to 21.7 mg/L, with a mean value of approximately 12.1 mg/L, reflecting typical AMN levels in municipal sewage entering the advanced AAO reactor. The average weekly effluent AMN concentrations consistently remained below 5 mg/L, with a mean of 1.8 mg/L. This demonstrates the advanced AAO reactor's capability to reliably reduce AMN to meet stringent effluent quality standards. The AMN removal efficiency curve exhibited consistently high performance, with an average efficiency exceeding 84% throughout the study period. It was observed that occurrence of temporary dips in efficiency during weeks 13 and 21, potentially linked to changes in influent loading. However, the advanced AAO reactor demonstrated strong recovery in subsequent weeks, highlighting its robustness and adaptability to fluctuating conditions.

Chen *et al.* observed AMN effluent concentrations below 0.5 mg/L in an A2/O-BAF system, indicating highly efficient nitrification [7]. Similarly, Zeng *et al.* reported that an A2O process achieved AMN levels consistently below 2 mg/L, aligning with stringent effluent discharge requirements [11]. Eghombi *et al.* and Vo *et al.* observed higher AMN effluent concentrations (~5 mg/L) in AAO-MBR and AAO/O systems, suggesting that process limitations, such as carbon availability and nitrate recycling ratios, impact nitrification performance [18, 20]. The observed high AMN removal performance aligns with findings by Lei *et al.*, who emphasized the critical role of optimized anoxic zones in facilitating effective denitrification [8]. This performance not only ensures compliance with effluent discharge standards but also significantly mitigates nutrient pollution in receiving water bodies, as emphasized by Izadi *et al.* [5]. The weekly average effluent $\text{NO}_3\text{-N}$ concentrations are illustrated in Figure 6.

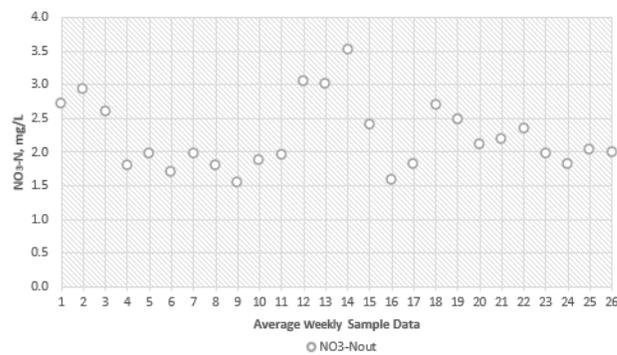


Figure 6 Nitrates concentration at effluent weekly average data

The average weekly $\text{NO}_3\text{-N}$ concentrations ranged from 1.5 to 3.5 mg/L, with an overall average of approximately 2.2 mg/L. These relatively consistent concentrations indicate effective denitrification in the anoxic zone, where nitrate generated during nitrification in the aerobic zone was efficiently reduced to nitrogen gas. Variations observed during weeks 12 to 14 suggest potential changes in influent characteristics, which may have temporarily affected denitrification performance.

As illustrated in Figure 4, COD levels during these weeks were below 250 mg/L, indicating that carbon availability in the anoxic zone was likely insufficient to fully support complete denitrification. This limitation resulted in slightly higher $\text{NO}_3\text{-N}$ concentrations in the effluent. Studies have also reported varying levels of $\text{NO}_3\text{-N}$ in treated effluent, influenced by factors such as carbon availability, anoxic zone conditions and nitrate recirculation rates. Zeng *et al.* documented low $\text{NO}_3\text{-N}$ concentrations (<2 mg/L) in an A2O system, demonstrating effective nitrogen removal through optimized anoxic conditions [11]. Similarly, Lei *et al.* reported $\text{NO}_3\text{-N}$ removal of 65.33%, with effluent concentrations ranging from 1.5 to 3.0 mg/L, highlighting the importance of sufficient carbon sources in facilitating complete denitrification [8]. Vo *et al.* and Eghombi *et al.* noted higher $\text{NO}_3\text{-N}$ effluent concentrations (~4–5 mg/L) in AAO/O and AAO-MBR systems, indicating suboptimal nitrate reduction due to limited organic carbon availability [18, 20]. These findings align with studies by Xiaolian *et al.* and Lei *et al.*, which emphasize the critical role of adequate carbon sources and optimized anoxic zone conditions in achieving effective denitrification [6, 8]. The influent and effluent TP concentrations, as well as removal efficiency trends, are presented in Figure 7.

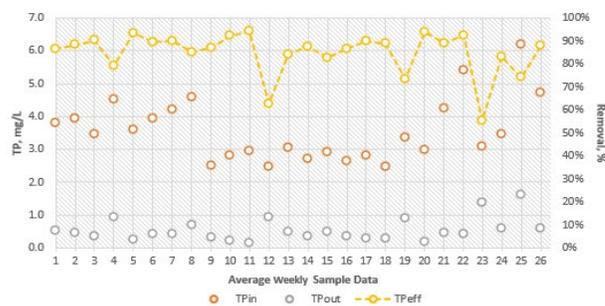


Figure 7 Difference in TP concentration and removal efficiency for influent and effluent weekly average data

The average weekly influent TP values ranged consistently between 2.4 and 6.1 mg/L, indicating consistent phosphorus loading in the influent sewage and reflecting typical phosphorus levels in the sewage. The average weekly effluent TP concentrations were significantly reduced, consistently averaging below 1.0 mg/L in most weeks. These low effluent TP values underscore the reactor's strong phosphorus removal capabilities, consistently meeting regulatory requirements.

The TP removal efficiency curve demonstrated consistently high performance, with an average efficiency exceeding 85% across the study period. Several minor dips in efficiency were observed, observed during weeks 12, 19 and 23 may be attributed to variations in influent phosphorus loading, DO concentration or insufficient carbon sources for optimal biological phosphorus removal. Despite these fluctuations, the advanced AAO reactor maintained robust overall performance, with effluent TP concentrations consistently well below the regulatory limit of 5 mg/L [2].

The average COD influent load was approximately 46,200 kg/day, with an effluent COD load of 2,622 kg/day, resulting in a COD removal efficiency of 94.3%. The COD/TN ratio was assessed to determine carbon availability for nitrate reduction, as denitrification requires a sufficient carbon source. The low effluent nitrate-nitrogen (NO_3^- -N) concentration of 2.2 mg/L suggests that sufficient COD was available to support complete denitrification, as demonstrated by the advanced AAO reactor's efficient COD removal. This indicates that nitrate accumulation in the effluent was minimal and that nitrate was successfully reduced in the anoxic zone.

For total phosphorus (TP) removal, polyphosphate-accumulating organisms (PAOs) require sufficient volatile fatty acids (VFAs) in the anaerobic zone to facilitate phosphorus release. The high TP removal efficiency (86.1%) confirms that enough carbon was available to sustain enhanced biological phosphorus removal (EBPR). The successful phosphorus uptake and storage in the aerobic phase further support this conclusion. If carbon limitations were present, we would expect reduced phosphorus uptake and higher effluent TP concentrations, but our results do not support this concern.

While carbon limitation was not observed in this study, we acknowledge that variations in influent characteristics or operational changes could impact carbon availability over time. To mitigate potential carbon constraints, the system can be optimized by adjusting the internal nitrate recirculation ratio or supplementing an external carbon source if the COD/TN ratio falls below the recommended threshold for efficient denitrification.

4.0 CONCLUSION

This study demonstrated the effectiveness of the advanced AAO reactor in treating municipal sewage, particularly in achieving high removal efficiencies for nutrient removal for TP, AMN and organic matter for COD. The advanced AAO reactor consistently maintained effluent concentrations that comply with stringent regulatory standards, including Standard A as specified in the Malaysia Sewerage Industry Guidelines (MSIG).

Over the 26-week of study period, the advanced AAO reactor achieved average removal efficiencies for COD, AMN and TP of 94.0%, 83.9% and 86.7% respectively. These results highlight the reactor's capability to mitigate nutrient discharge, thereby

reducing the risk of eutrophication in receiving water bodies. The performance of the advanced AAO reactor was evaluated based on actual incoming sewage flow of 170 MLD under variable influent conditions of a full-scale plant configuration which underscored its robustness and reliability for large-scale municipal applications.

The findings suggested that the advanced AAO reactor is a viable and sustainable solution for modern sewage treatment, capable of addressing both nitrogen and phosphorus concentration in the effluent discharge of conventional STPs.

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Conflict of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

References

- [1] Metcalf & Eddy, 2014. *Wastewater Engineering: Treatment and Resource Recovery*, 5th ed. McGraw-Hill Education.
- [2] National Water Services Commission (SPAN), 2009. *Malaysian Sewerage Industry Guideline: Sewage Treatment Plant*, Vol. IV, 3rd ed. National Water Services Commission (SPAN), Putrajaya, Malaysia.
- [3] National Water Services Commission (SPAN), 2020. *Water and Sewerage Fact Book 2020*. National Water Services Commission (SPAN), Putrajaya, Malaysia. Available: <https://www.span.gov.my/document/upload/ANpj5zmwoMX45KLGdfPcqMTJjoCRdKOW.pdf>
- [4] Government of Malaysia, 2009. *Environmental Quality Act 1974 (Act 127) and Environmental Quality (Sewage) Regulations 2009*. Attorney General's Chambers of Malaysia, Kuala Lumpur, Malaysia.
- [5] P. Izadi and A. Eldyasti, 2020. "Design, operation and technology configurations for enhanced biological phosphorus removal (EBPR) process: a review," *Reviews in Environmental Science and Bio/Technology*, 19(4): 561–593. DOI: 10.1007/s11157-020-09538-w.
- [6] W. Xiaolian, P. Yongzhen, W. Shuying, F. Jie, and C. Xuemei, 2006. "Influence of wastewater composition on nitrogen and phosphorus removal and process control in A2O process," *Bioprocess and Biosystems Engineering*, 28(6): 397–404. DOI: 10.1007/s00449-006-0044-5.
- [7] Y. Chen, C. Peng, J. Wang, L. Ye, L. Zhang, and Y. Peng, 2011. "Effect of nitrate recycling ratio on simultaneous biological nutrient removal in a novel anaerobic/anoxic/oxic (A2/O)-biological aerated filter (BAF) system," *Bioresource Technology*, 102(10): 5722–5727. DOI: 10.1016/j.biortech.2011.02.114.
- [8] S. Lei, J. Zhao, J. Zhao, S. Xie, J. Zhang, and B. Shi, 2022. "Optimization of A2O process by changing anoxic tank volume based on GPS-X simulation," *Research Square*. DOI: 10.21203/rs.3.rs-2058607/v1.
- [9] F. Fang et al., 2016. "Quantitative evaluation of A2O and reversed A2O processes for biological municipal wastewater treatment using a projection pursuit method," *Separation and Purification Technology*, 166: 164–170. DOI: 10.1016/j.seppur.2016.04.036.
- [10] K. Wang et al., 2023. "Comparison on biological nutrient removal and microbial community between full-scale anaerobic/anoxic/aerobic

- process and its upgrading processes," *Bioresource Technology*, 374: 128757. DOI: 10.1016/j.biortech.2023.128757.
- [11] W. Zeng, L. Li, Y. Yang, S. Wang, and Y. Peng, 2010. "Nitritation and denitritation of domestic wastewater using a continuous anaerobic-anoxic-aerobic (A2O) process at ambient temperatures," *Bioresource Technology*, 101(21): 8074–8082. DOI: 10.1016/j.biortech.2010.05.098.
- [12] X. Meng et al., 2013. "A full-scale anaerobic-anoxic-aerobic process coupled with low-dose ozonation for performance improvement," *Bioresource Technology*, 146: 240–246. DOI: 10.1016/j.biortech.2013.07.045.
- [13] S. Chakraborty and H. Veeramani, 2006. "Effect of HRT and recycle ratio on removal of cyanide, phenol, thiocyanate and ammonia in an anaerobic-anoxic-aerobic continuous system," *Process Biochemistry*, 41(1): 96–105. DOI: 10.1016/j.procbio.2005.03.067.
- [14] J. C. Leyva-Díaz, M. M. Muñío, J. González-López, and J. M. Poyatos, 2016. "Anaerobic/anoxic/oxic configuration in hybrid moving bed biofilm reactor-membrane bioreactor for nutrient removal from municipal wastewater," *Ecological Engineering*, 91: 449–458. DOI: 10.1016/j.ecoleng.2016.03.006.
- [15] S. Ge, Y. Zhu, C. Lu, S. Wang, and Y. Peng, 2012. "Full-scale demonstration of step feed concept for improving an anaerobic/anoxic/aerobic nutrient removal process," *Bioresource Technology*, 120: 305–313. DOI: 10.1016/j.biortech.2012.06.030.
- [16] J. Wang, K. Chon, X. Ren, Y. Kou, K. J. Chae, and Y. Piao, 2019. "Effects of beneficial microorganisms on nutrient removal and excess sludge production in an anaerobic-anoxic/oxic (A2O) process for municipal wastewater treatment," *Bioresource Technology*, 281: 90–98. DOI: 10.1016/j.biortech.2019.02.047.
- [17] W. Zhao, Q. Sui, X. Mei, and X. Cheng, 2018. "Efficient elimination of sulfonamides by an anaerobic/anoxic/oxic-membrane bioreactor process: performance and influence of redox condition," *Science of the Total Environment*, 633: 668–676. DOI: 10.1016/j.scitotenv.2018.03.207.
- [18] D. T. Vo et al., 2022. "Application of an anaerobic-anoxic-oxic-oxic (AAO/O) model to the treatment of real domestic wastewater," *Journal of Chemistry*, 2022: 9456026. DOI: 10.1155/2022/9456026.
- [19] Z. Zhou et al., 2011. "Simulation and performance evaluation of the anoxic/anaerobic/aerobic process for biological nutrient removal," *Korean Journal of Chemical Engineering*, 28(5): 1233–1240. DOI: 10.1007/s11814-010-0502-2.
- [20] E. Eghombi et al., 2022. "Efficient phosphorus recovery from municipal wastewater using enhanced biological phosphorus removal in an anaerobic/anoxic/aerobic membrane bioreactor and magnesium-based pellets," *Membranes*, 12(2): 210. DOI: 10.3390/membranes12020210.
- [21] F. Li et al., 2019. "Research on operation efficiency and membrane fouling of A2/O-MBR in reclaimed water treatment," *Membranes*, 9(12): 172. DOI: 10.3390/membranes9120172