Semarak International Journal of Applied Sciences and Engineering Technology

Journal homepage: https://semarakilmu.my/index.php/sijaset
ISSN: 3030-5314

Nutrient Removal Evaluation of Advanced Anaerobic-Anoxic-Oxic (Aao) in Sewage Treatment

Jeffrey Heng Yuen Too[1,*], Shreeshivadasan Chelliapan[2]

[1] Loyal Engineering Sdn. Bhd., Level 29-02, Tower B, The Vertical Business Suite, No.8, Jalan Kerinchi, Bangsar South 59200 Kuala Lumpur, Malaysia.
[2] Department of Smart Engineering and Advanced Technology, Faculty of Artificial Intelligence, Universiti Teknologi Malaysia, 54100, Jalan Sultan Yahya Petra, Kuala Lumpur, Malaysia.

ARTICLE INFO

Article history:
Received 20 March 2025
Received in revised form 30 April 2025
Accepted 25 May 2025
Available online 15 July 2025

Keywords:
Advanced AAO; nutrient removal; biological phosphorus removal

ABSTRACT

Nutrient pollution from untreated or inadequately treated sewage remains a critical environmental issue, which contributes to eutrophication and the degradation of aquatic ecosystems. In Malaysia, the removal of phosphorus and nitrogen is particularly challenging due to reliance on conventional treatment methods. This study presented a performance evaluation of an advanced Anaerobic-Anoxic-Oxic (AAO) reactor implemented full-scale Sewage Treatment Plant (STP) in Kuala Lumpur which is the first of its kind technology in the country. The reactor operated at an average capacity of 170 Million Liters per Day (MLD) and was assessed over 26 weeks under actual sewage loading conditions. The reactor was integrated with a pre-anoxic zone for improved denitrification and it utilizes biological nutrient removal (BNR) mechanisms without chemical additives for nutrient removal. Results demonstrated high removal efficiencies: 96.7% for Biological Oxygen Demand (BOD_{5}), 94.0% for Chemical Oxygen Demand (COD), 83.9% for Ammoniacal Nitrogen (AMN), 64.2% for Total Nitrogen (TN) and 86.7% for Total Phosphorus (TP). The treated effluent consistently complied with discharge limits, with average concentrations of 2.8 mg/L BOD_5, 15.4 mg/L COD, 1.7 mg/L AMN, 6.5 mg/L TN and 0.5 mg/L TP. These findings confirm the advanced AAO reactor's robustness in handling variable influent loads while maintaining effluent quality within regulatory discharge standards. This study also fills a critical knowledge gap by providing empirical data on full-scale BNR performance in Malaysia.The results support the advanced AAO reactor as a scalable and environmentally sustainable alternative to conventional treatment offering a practical pathway for future STP upgrades and compliance with emerging nutrient discharge regulations.

1. Introduction

Water, an essential resource for life, is vital for sustaining human survival and biodiversity of our planet earth. Water is being distributed to our communities for daily applications. However, after using the water, it becomes a carrier of waste, where a proper treatment before it can be reused or

* *Corresponding author.*
E-mail address: jeffreyheng@graduate.utm.my

https://doi.org/10.37934/sijaset.6.1.1729

safely discharged. Sewage contains nutrients such as nitrogen and phosphorus, which can adversely affect aquatic plants. Moreover, it may contain toxic compounds with the potential for mutagenic or carcinogenic effects [1].

According to the environmental quality report by the Department of Environmental (DOE) Malaysia, as of 2020, the report indicates that 66% of these rivers in that study was exhibiting good water quality, while 29% are slightly polluted and 5% are classified as polluted [2]. Excessive nutrient levels in the rivers can lead to algae blooming, causing low oxygen levels in the water bodies. This phenomenon has widespread implications, affecting ecological balance, public health and the overall environmental condition. The excessive release of nutrients is a major contributor to environmental problems such as eutrophication. Phosphorus is one of the key nutrients for the growth of microorganisms in the water body, but in excess can lead to eutrophication [3]. For mitigating this nutrient pollution, regulations governing nutrient discharges are progressively tightening to address these concerns [4]. The introduction of biological nutrient removal processes has been widely accepted and applied globally for the combined removal of nitrogen and phosphorus, mainly due to its economic advantages over chemical treatment methods [5]. In Malaysia, the conventional processes approved under the Malaysia Sewerage Industry Guidelines Volume IV (MSIG) consists of Extended Aeration Activated Sludge (EAAS), Sequencing Batch Reactor (SBR), Conventional Activated Sludge (CAS) and Hybrid Systems where all of them are categorized under the suspended growth treatment method [6]. In addition to the MSIG approved processes, other CAS processes like Step Feed CAS (Anoxic-Oxic-Anoxic-Oxic) are also utilized, specifically for nitrogen removal [7]. Currently, the effluent discharge standards for rivers and streams in Malaysia do not mandate the removal of TP unless the discharge is directed into stagnant water bodies or lakes. In recent years, advancements in sewage treatment technologies have led to the widespread adoption of the AAO process globally, owing to its simplicity and effectiveness in simultaneously removing nutrients and organic compounds within a single compartmentalized reactor [8].

The AAO process is a conventional method for biological treatment of sewage which has the capability of removing organic pollutants and nutrients such as nitrogen and phosphorus from the sewage. The process involved is nitrification, denitrification and phosphorus removal, making it a widely utilized technology in Sewage Treatment Plants (STPs) [9]. This process has been widely used in many STP as this process is simple and has the capability of removing nitrogen, phosphorus and other organics compositions in the sewage [10]. Over the years, there have been several modified versions of the AAO process where it achieved remarkable sewage treatment efficiency compared to the conventional AAO process. A study on the modified AAO process shows that the removal efficiency for Chemical Oxygen Demand (COD), Ammoniacal Nitrogen (AMN) and Total Phosphorus (TP) are 89.36%, 96.89% and 95.99% respectively [8]. While another study evaluated the performance of seven (7) Nos. of AAO plants, finding that the effluent consistently achieved TN concentrations below 20 mg/L and TP concentrations below 1 mg/L [11]. Literature reviews have also revealed that the conventional or modified version of AAO process exhibits high efficiency in removing organic pollutants, achieving removal rates up to 89% for COD, 82.6% for BOD_5 and 84.85% for AMN [12]. Additionally, TN and TP efficient removal reaching up to 50.4% and 85.1% respectively. The TN removal efficiency is influenced by the nitrates of the Internal Mixed Liquor Recycle (IMLR) recycled back to the anoxic zone. The required IMLR varies from 100% to 400% with a RAS of 100% which depends on the TN removal requirement [13]. Higher TN removal rates may lead to higher IMLR rates. Moreover, studies also indicated that the AAO process can effectively treat low-strength sewage with a C/N ratio below 3.0, although the impact of DO levels on TP removal efficiency should be considered as well [14]. Despite the extensive research on AAO and its modified configurations, most prior studies in the literature review have been limited to pilot-scale or laboratory conditions, with no evidence from full-scale implementations for sewage characteristics like Malaysia. Furthermore, no prior study has systematically evaluated the process's ability to achieve Standard A discharge compliance based on Malaysia's discharge standard using purely biological nutrient removal without chemical additives for TP removal using actual sewage conditions Malaysia. This study is the first to evaluate the real-world performance of an advanced AAO reactor operating at full scale (170 MLD) in Malaysia. It uniquely examines the reactor's ability to meet Standard A effluent discharge limits solely through biological nutrient removal without chemical additives. The key objectives of this study are to assess the nutrient and organic matter removal efficiencies under actual influent conditions and compliance with Malaysia's effluent discharge standards.

The advanced AAO reactor is made up of four major zones: the Pre-Anoxic Zone, the Anaerobic zone, followed by the Anoxic zone, and lastly the Aerobic zone. These zones are specifically designed to establish unique environmental conditions to favor different microorganism growth that facilitate three key biological processes: TN removal, TP removal and the breakdown of organic matter (BOD_5 & COD). This configuration facilitates a comprehensive treatment process using simple processes and minimal structures. Figure 1 illustrates the typical arrangement of the advanced AAO reactor proposed for this study.

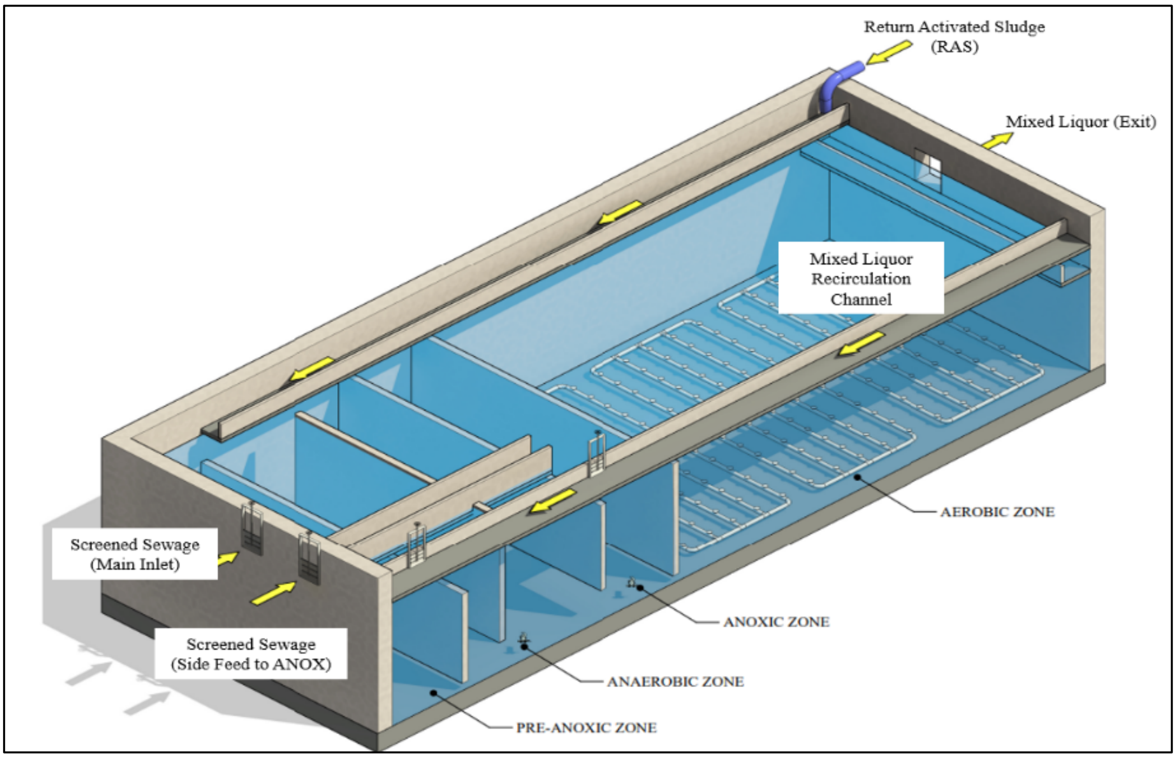

Fig. 1. The advanced AAO sewage treatment plant major components

The sewage flows into the first zone after completion of preliminary treatment, which is the pre-anoxic zone, serving as an anoxic selector. This zone creates a high microorganism environment to limit the growth of filamentous microorganisms which increases the possibility of bulking sludge in the secondary clarifier tank at the downstream of the advanced AAO reactor. The settled sludge from the secondary clarifier is then recycled back to this zone using mechanical pumping as Returned Activated Sludge (RAS). Within the pre-anoxic zone, the RAS is mixed with the influent sewage using submersible mixers, favoring denitrifying microorganisms to consume nitrites within the RAS, thus enhancing the downstream anaerobic zone treatment process.

After the pre-anoxic zone, the sewage will enter the Anaerobic zone, where Polyphosphate Accumulating Organisms (PAOs) plays a role of breaking down polyphosphates within their cells and absorb organic compounds like fatty acids from the sewage. This process leads to the release of phosphorus under anaerobic conditions [15]. In the Anoxic zone, denitrifying microorganisms use the organic carbon present in sewage as an electron donor and nitrate as an electron acceptor during anaerobic respiration, resulting in the release of nitrogen gas [9]. Similar to the other non-aerated zones, submersible mixers are installed within the reactor to maintain suspension of the mixed liquor and provide homogeneous mixing for better treatment efficiency.

In the aerobic zone, organic matter (BOD_5 & COD) removal is achieved through the absorption and metabolism of microorganisms degrading organic matter. Nitrification also occurs, converting AMN to nitrite and nitrate as part of the biological nitrogen removal process [16]. Compressed air is injected into the aerobic zone, diffused by submersible disc diffusers to enhance oxygen transfer in the sewage through fine bubbles aeration method. Throughout the study, the Dissolved Oxygen (DO) level in the aerobic reactor was kept within 2.0 mg/L. The RAS was operated at approximately 50 to 100% of the incoming flow rate to maintain sufficient MLSS within the reactor. The IMLR was operated between 100% to 200% of the incoming flow rate for nitrogen removal process.

The advanced AAO reactor for this study has several improvements compared to the conventional process where it has included a pre-anoxic zone upstream of the AAO reactor. This design allows the nitrate recycle pathway to be redirected to either the anoxic zone or the pre-anoxic zone, enhancing nutrient removal efficiency. Additionally, part of the incoming sewage can be diverted to the anoxic reactor as a carbon source, optimizing the denitrification process by addressing nutrient imbalances that may otherwise hinder its efficiency.

Despite progress in sewage treatment technologies, optimizing nutrient removal efficiency, particularly for nitrogen and phosphorus, within a single reactor system remains a challenge. Conventional systems approved by Suruhanjaya Perkhidmatan Air Negara (SPAN) are limited in their ability to effectively remove TP from sewage. Biological phosphorus removal offers a more sustainable alternative to chemical precipitation, which not only increases operational costs but also places an additional financial burden on sewage operators. The findings will offer valuable insights into the actual performance of the advanced AAO reactor in full scale operation treating actual sewage characteristic, demonstrating its ability to meet stricter effluent discharge standards by effectively removing both TN and TP, while reducing the environmental impact of nutrient-rich wastewater in Malaysia.

2. Methodology

An existing STP which has adopted the advanced AAO reactor, located in Kuala Lumpur, was utilized for this study and it represents the first plant in Malaysia to implement the advanced AAO biological nutrient removal process. During the study, the plant was operated at an average hydraulic inflow of 170.0 ± 19.0 MLD which requires compliance with effluent discharge standard A as outlined in the MSIG requirements [10]. The raw sewage was transferred from an inlet pumping station, where the pumping flow distribution was divided between two STPs. The advanced AAO STP was equipped with advanced pretreatment systems, including a rotary drum screen for fine screening, vortex grit separation and an aerated grease removal system. A total of four advanced AAO reactors were in operation during this study period. The effluent from the advanced AAO reactor was discharged into a secondary clarifier tank and then to an effluent pumping station to be lifted to the effluent sampling point before discharge into the receiving wate body.

2.1 Influent Sewage

The sewage characteristics were analyzed based on the collected influent samplings and a statistical analysis was conducted for this study. Both influent and effluent sewage characteristics of the advanced AAO reactor were evaluated based on key parameters for BOD_5, COD, AMN, TN and TP. The incoming sewage characteristic has been summarized in Table 2.

2.2 Analytical Method

The raw incoming sewage of the plant was collected at the upstream of the secondary fine screen after entering the common channel of the plant before the advanced AAO reactor. The treated effluent was collected at the dedicated sampling location after passing through the ultraviolet disinfection chamber, just before being discharged back into receiving water body. Daily samples were collected and analyzed in the laboratory. The sampling period of 26 weeks to monitor the influent sewage condition and the quality of the treated effluent. The results were summarized on a weekly basis for evaluation of the performance of the advanced AAO reactor. The following table summarized the testing method for both influent and effluent sampling for this study.

Table 1
Standard methods and references for key wastewater parameters

Parameter	Standard Method
COD	Reactor Digestion Method of HACH 8000
BOD_5	Dilution Method of HACH 8043
AMN	Salicylate Method of HACH 8155
TN	Persulfate Digestion Method of HACH 10071
TP	Acid Hydrolysis Method of HACH 8180

2.3 Pollutant Removal Analysis

The calculated removal efficiencies for the pollutant to assess the performance of the advanced AAO reactor was calculated using the following formula:

$$RE = \frac{Cin - Cout}{Cin} \; x \; 100\% \qquad (1)$$

Where:
RE = Removal Efficiency
C_{in} = Influent Sampling Concentration in mg/L
C_{out} = Effluent Sampling Concentration in mg/L

The RE was then compared with the EQA requirement for Standard A for evaluating the compliance of the advanced AAO reactor and summarized on a weekly basis.

3. Results and Discussion

In this study, actual sewage was fed into the advanced AAO reactor where it undergoes pretreatment before entering the advanced AAO reactor. The source of sewage was collected within the sewerage network catchment to the inlet pumping station, where the influent sewage characteristics are shown in Table 2.

Table 2
Statistical Analysis of The Influent Sewage Characteristics

Parameter	Unit	Min	Ave	Max	Std Dev
BOD_5	mg/L	30.0	93.2	208.5	27.3
COD	mg/L	108.0	271.2	491.0	67.1
AMN	mg/L	2.1	11.2	25.9	4.9
TN	mg/L	7.8	19.0	30.4	4.6
TP	mg/L	1.1	3.6	9.3	1.3

Based on the analysis, the incoming sewage BOD_5 levels ranged from a minimum of 30.0 mg/L to a maximum of 208.5 mg/L, with an average of 93.2 mg/L and a standard deviation of 27.3 mg/L. For COD concentrations exhibited a wider range, varying from 108.0 mg/L to 491.0 mg/L, with an average of 271.2 mg/L and a standard deviation of 67.1 mg/L. As for nutrient portion, the AMN which represents nitrogenous pollutants, ranged from 2.1 mg/L to 25.9 mg/L, with an average value of 11.2 mg/L and a standard deviation of 4.9 mg/L. For TN concentration of the influent sewage, the average of 19.0 mg/L and a standard deviation of 30.4 mg/L. Similarly, influent TP concentrations ranged from 1.1 mg/L to 9.3 mg/L, with an average of 3.6 mg/L and a standard deviation of 1.3 mg/L. These results highlight the variability and strength of the influent sewage, emphasizing the need for effective nutrient removal mechanisms in the sewage treatment process to address environmental concerns and meet regulatory discharge standards. The variability in these parameters reflects the dynamic characteristic of the incoming sewage and the evaluation for the performance of the advanced AAO system in handling these challenges. The evaluation of the advanced AAO reactor was achieved by observing the concentrations for the key parameters including BOD_5, COD, AMN, TN and TP. The average sewage condition and treatment efficiency are summarized in Table 3.

Table 3
Sewage inlet and treated effluent condition and removal rates

Description	Unit	BOD_5	COD	AMN	TN	TP
Average inlet	mg/L	93.2 ± 27.3	271.2 ± 67.1	11.2 ± 4.9	19.0 ± 4.6	3.6 ± 1.3
Average outlet	mg/L	2.8 ±.1.2	15.4 ±. 6.8	1.7 ±.1.0	6.5 ±.2.7	0.5 ±. 0.3
Effluent Standard A[a]	mg/L	< 20	< 120	< 10	< 20[b]	< 5
Average removal efficiency	mg/L	96.7 ±.1.9	94.0 ±.3.1	83.9 ±.10.2	64.2 ±.16.1	86.7 ±.7.9

[a] Effluent Standard as per MSIG Volume IV Section 3, Table 3.2 - Design Effluent Values
[b] Design Value for Effluent TN Discharge Value

Table 3 summarized the average concentrations of key parameters at the inlet and outlet of the advanced AAO reactor, along with the corresponding pollutant removal efficiencies. The results demonstrated that the effluent concentrations complied with the effluent requirement, highlighting the effectiveness of the advanced AAO reactor in meeting DOE discharge standards. This achievement underscored the advanced AAO reactor’s capability to deliver reliable and efficient sewage treatment while ensuring environmental protection to the receiving water body. The tropical ambient temperatures likely promoted stable microbial kinetics, especially for nitrification and EBPR organisms, reducing the risk of seasonal performance drops observed in temperate regions as Malaysia climate does not fluctuate throughout the year [17].

3.1 Performance Evaluation of Organic Matter Removal

The inlet and outlet levels of BOD_5 in the sewage are illustrated in Figure 2 on an average weekly basis, along with the removal efficiency for the advanced AAO reactor. During the study period, the average influent BOD_5 concentration was recorded at 93.23 ± 27.29 mg/L. The treated effluent consistently showed BOD_5 concentrations ranging from 1.00 to 7.60 mg/L, thereby meeting the permissible discharge standard of less than 20 mg/L. The achieved average BOD_5 removal rate of 96.7 ± 1.9% indicates effective consumption of BOD_5 during denitrification processes, with the remaining BOD_5 efficiently oxidized by aerobic microorganisms in the aerobic process. The BOD_5 removal efficiency observed in this study, surpasses those reported in similar systems such as the AAO/O configuration by Vo *et al.*, [14] which achieved approximately 82.6% efficiency, and aligns favourably with pilot-scale AAO systems by Lopes *et al.*, [12] which typically range between 85–95%. Unlike membrane-assisted systems such as the A1/A2/O-MBR used by Zhao *et al.*, which focused primarily on antibiotic removal, the advanced AAO reactor in this study achieved stable BOD_5 effluent concentrations well below the regulatory threshold, demonstrating high resilience and treatment efficacy under actual Malaysian sewage loads [17].

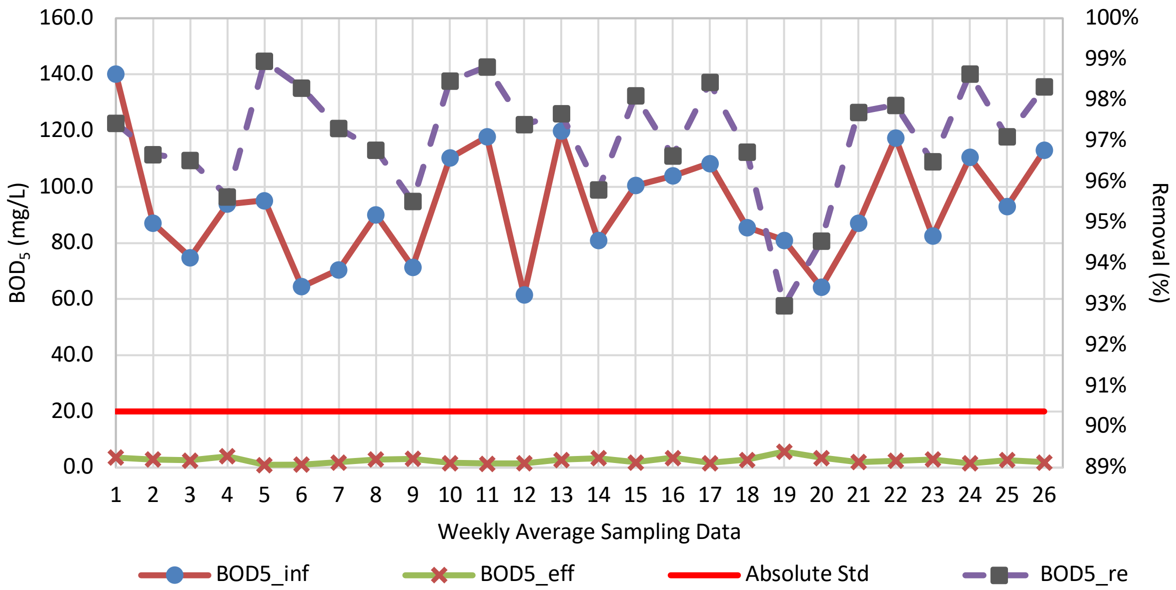

Fig. 2. BOD_5 influent, effluent sampling and removal efficiency during the study period

Figure 3 illustrated the COD levels at the inlet and outlet of the advanced AAO reactor, along with the removal efficiency achieved on an average weekly basis. Throughout the study period, the average influent COD concentration was 271.8 ± 67.11 mg/L, while the treated effluent consistently maintained COD concentrations between 3.0 and 42.0 mg/L, well below the permissible discharge limit of 120 mg/L. The average COD removal efficiency of 94.0 ± 3.1% reflected the effective degradation of biodegradable COD during the anaerobic reactor phase and its subsequent utilization in denitrification processes. The remaining COD was effectively removed through oxidation, ensuring the effluent from the advanced AAO reactor met the required quality standards. This performance is comparable to or surpasses that of other reported AAO-based systems, such as the pilot-scale configuration in Lopes *et al.,* [12] which achieved typical COD removals of 85–90%, and the modified AAO/O system in Vo *et al.*, [14] which achieved COD reductions of approximately 71.8%.

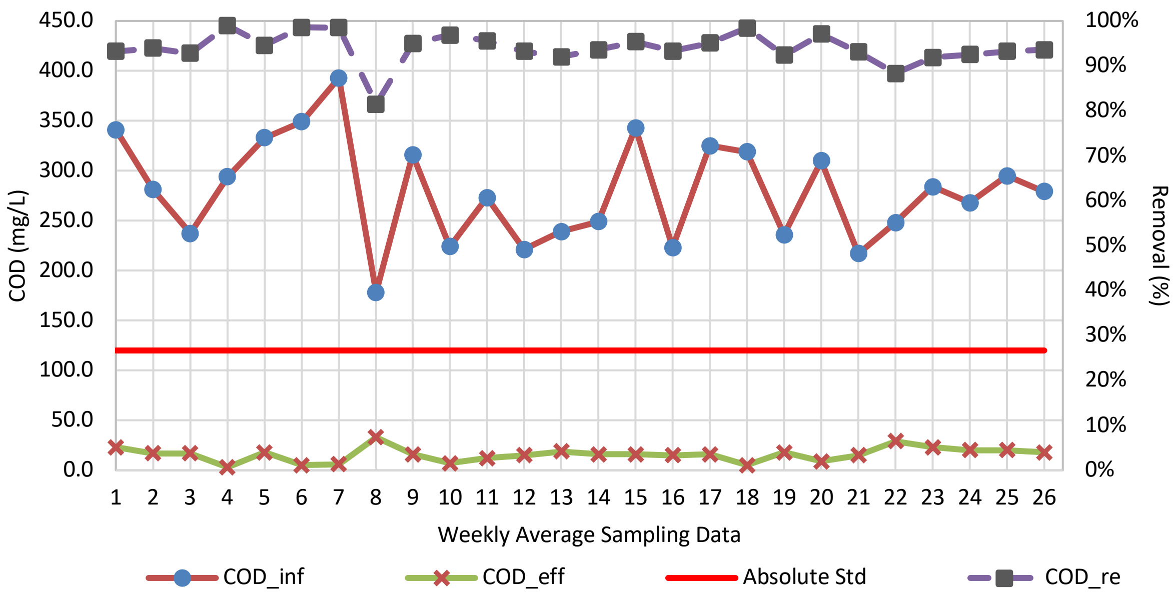

Fig. 3. COD influent, effluent sampling and removal efficiency during the study period

The organic matter removal efficiencies observed in this study substantiate the effectiveness of the advanced AAO configuration under real-world operating conditions. The system achieved an average COD removal efficiency of 94.0 ± 3.1% and BOD_5 removal of 96.7 ± 1.9%, with effluent concentrations well within the regulatory discharge limits. These findings are in close agreement with values reported in the literature review, where COD removal efficiencies typically range from 91% to 96% in optimized biological nutrient removal systems [3,13]. Vo *et al.,* [14] reported a COD removal efficiency of 95.9% in a household-scale AAO-O system treating domestic sewage, highlighting the benefit of extending oxic retention time and incorporating membrane filtration [14]. Similarly, Lopes *et al.,* [12] demonstrated COD removal rates approaching 95% in a pilot AAO system treating high-strength industrial wastewater. While the advanced AAO reactor in this study operated under full-scale conditions with variable influent loads and without membrane support. Unlike controlled lab-scale systems, the advanced AAO reactor in this study operated under fluctuating hydraulic and organic loading conditions typical of municipal settings yet consistently met effluent discharge requirements. The A1/A2/O-MBR process evaluated by Zhao *et al.,* [17] recorded a COD removal efficiency of 96.5%, with performance gains attributed to extended sludge retention time and membrane polishing. However, such systems are energy-intensive and may not be economically viable for municipal-scale applications in resource-constrained settings. In contrast, the advanced AAO reactor in this study achieved stable effluent quality without chemical or membrane support, reflecting a more sustainable operational model.

As for BOD_5 removal, CAS systems generally report removal efficiencies between 85% and 92%, depending on influent composition and aeration strategy [1]. The advanced AAO system outperformed these baselines, achieving effluent BOD_5 concentrations as low as 1.0 mg/L. This surpasses values typically reported in SBR systems (93–94% efficiency, 10–15 mg/L effluent) reported by Pham *et al.*, [7] and Zhao *et al.,* [17] reported that the performance of MBR-based systems using AAO configurations, which often achieved over 96% BOD_5 removal and 5–10 mg/L effluent concentrations. Nevertheless, MBR systems entail higher capital and operational costs due to membrane maintenance, which limits their deployment in large-scale municipal contexts.

Overall, the empirical results obtained from this study reinforce existing literature on the efficiency of AAO-based configurations for organic matter removal, while offering new insights into their reliability under full-scale, variable-load conditions without reliance on chemical precipitation or membrane filtration. This highlights the potential of the advanced AAO process as a sustainable alternative for municipal sewage treatment in tropical regions. The observed effluent COD and BOD_5 levels were consistently below the discharge Standard A limits, reinforcing the process's applicability to national compliance frameworks.

3.2 Performance Evaluation of Nutrient Removal

The study also focused on the nutrient removal for AMN, TN and TP in the sewage. Throughout the study, the average AMN concentration in the influent was 11.2 ± 4.9 mg/L, with the maximum concentration reaching 25.9 mg/L. Despite fluctuations in the influent concentration, as depicted in Figure 4., the advanced AAO reactor consistently achieved compliance with the effluent AMN levels ranging from 0.3 to 4.9 mg/L. The observed average removal rate of 83.9 ± 10.2% complied with the Standard A effluent discharge requirements of less than 10 mg/L. The effective AMN removal observed due to well-integrated nitrification and denitrification zones. Nitrification is facilitated by aerobic conditions in the final oxic zone, converting ammonium into nitrate, while denitrification occurs in the preceding anoxic zone, reducing nitrate to nitrogen gas. This spatial phase segmentation mirrors the successful nutrient removal configurations reported by Lopes *et al.*, [12].who observed comparable nitrogen removal in a pilot AAO system treating industrial wastewater

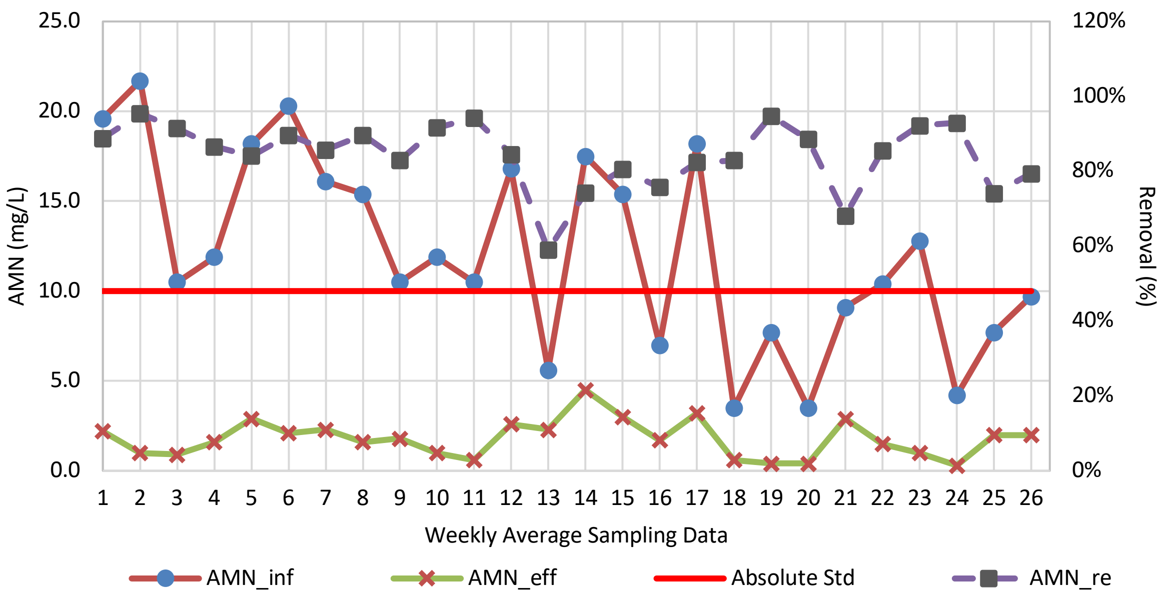

Fig. 4. AMN influent, effluent sampling and removal efficiency during the study period

Figure 5 illustrates the TN concentrations in both the influent and effluent sewage, alongside the corresponding removal efficiency. During the study, the average influent TN concentration was measured at 19.0 ± 4.6 mg/L, which was already below the design limit of 20 mg/L compared to the design value of 50 mg/L. The treated effluent consistently maintained TN concentrations between 1.5 and 15.7 mg/L, with an average of 6.5 mg/L, successfully meeting the design standard. The advanced AAO reactor achieved an average TN removal efficiency of 64.2 ± 16.1%, demonstrating its capability to effectively reduce TN levels at the point of discharge. The TN removal performance of the advanced AAO reactor is attributed to its integrated biological processes, which facilitate both nitrification and denitrification. Comparable findings were reported by Lopes *et al.*, [12] who documented TN removal in an AAO pilot plant treating high-strength slaughterhouse wastewater, where recirculation rate and HRT were critical to achieving high nitrogen removal. Similarly, Zhang *et al.,* [8] achieved superior TN removal efficiency in an improved AAO process employing a regulated influent regime and optimized phase distribution. The relatively modest removal efficiency in the present study may be partially explained by the low initial TN concentration, which can limit the substrate availability for denitrifying bacteria, as noted in Lei *et al.,* [9] simulation-based optimization of AAO processes. Nevertheless, the performance of the advanced AAO reactor under actual field conditions without supplemental carbon dosing or membrane support highlights its practical effectiveness in achieving TN reduction for moderate-strength municipal sewage. Compared to conventional treatment methods, the advanced AAO reactor offers enhanced nutrient removal capability for meeting effluent discharge standards.

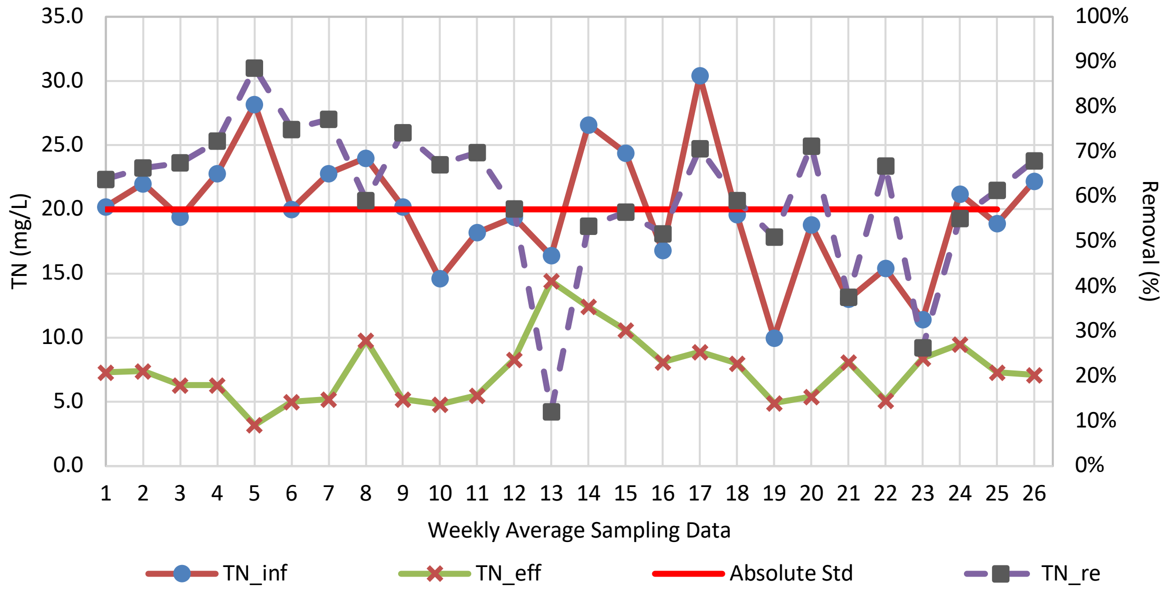

Fig. 5. TN influent, effluent sampling and removal efficiency during the study period

Figure 6 presents the concentrations of TP in both the influent and effluent sewage, along with the corresponding removal efficiency. During the study period, the average influent TP concentration was recorded at 3.6 ± 1.3 mg/L, which was already below the regulatory limit of 5 mg/L. The treated effluent consistently exhibited TP concentrations ranging from 0.1 to 1.9 mg/L, with an average of 0.5 mg/L, meeting the discharge standard of less than 5 mg/L. The average TP removal efficiency of 86.7 ± 7.9% underscored the effectiveness of the advanced AAO reactor in significantly reducing TP levels for effluent compliances. The performance aligns closely with that reported in Vo *et al.*, [14] where a modified AAO/O system achieved a TP removal efficiency of 91.9% treating domestic sewage. Zhao *et al.,* [17] also documented high phosphorus removal in an AAO-MBR system, benefiting from extended sludge retention and membrane polishing. In addition, Zhang *et al.,* [8] observed TP removal efficiencies of 95.99% in an improved AAO system incorporating a pre-anaerobic tank and regulated influent flow, emphasizing the role of process design in optimizing phosphorus removal. Lei *et al.,* [9] using simulation modelling, demonstrated that adjusting the anoxic and aerobic tank volumes can further enhance TP removal by optimizing microbial retention and phase sequencing. While the TP removal rate in this study is slightly lower than those reported in lab-scale or membrane-based systems, it remains highly satisfactory for a full-scale municipal reactor operating without chemical additives or advanced polishing units.

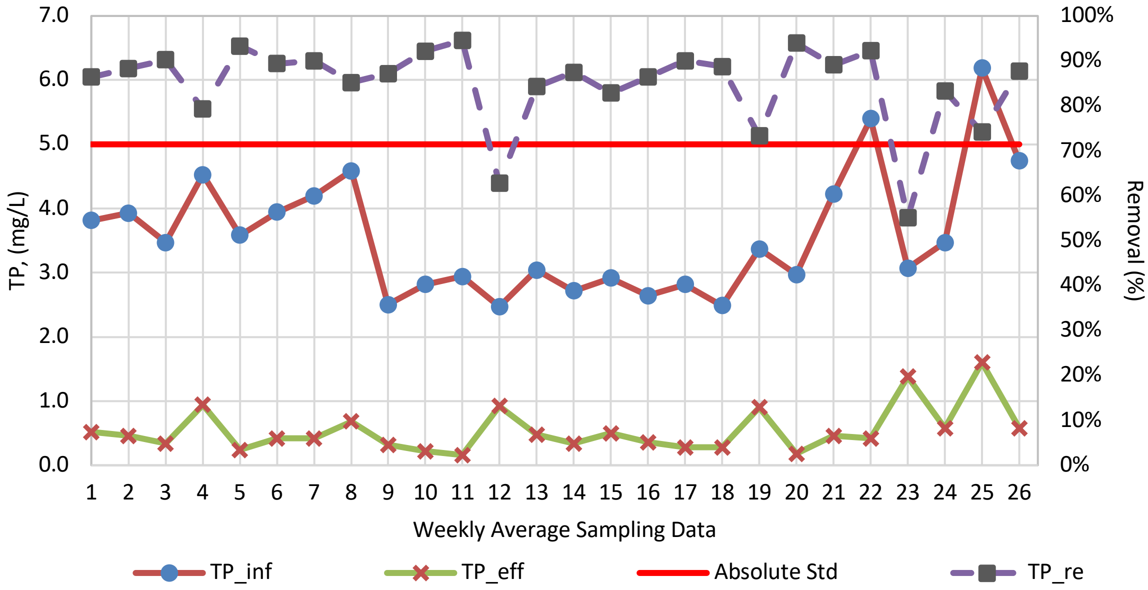

Fig. 6. TN influent, effluent sampling and removal efficiency during the study period

Throughout the 26-week study period, all weekly-averaged samples demonstrated 100% compliance with Malaysia's Effluent Discharge Standard A for both organic and nutrient parameters. The influent sewage characteristics revealed a favourable BOD_5:TN ratio of 5.2:1, supporting efficient biological oxidation for nitrogen removal, and a BOD_5:TP ratio of 30:1, conducive to enhanced biological phosphorus removal (EBPR). These conditions contributed to the consistent performance of the advanced AAO reactor, which effectively removed organic matter and nutrients under real municipal loading. The average AMN removal efficiency was 83.9%, closely matching the 84% reported by Lopes *et al.*, and falling within expected performance ranges for aerobic–anoxic configurations [12]. However, this value was substantially lower than the 99.3% by Vo *et al.* and 96.61% observed by Guo *et al.*, both of which involved enhanced AAO or membrane-aided designs [14,18]. This difference likely stems from variation in operational strategies, particularly DO control, aeration intensity, HRT and sewage temperature that possible to affect nitrification performance.

As for TN, the average removal efficiency was 64.2%, which is modest compared to the 93.6% by Vo *et al.,* [14] and 69–79% range observed by Wang *et al.,* [19]. Notably, Zhao *et al.,* [17] demonstrated TN removal efficiencies above 84% using an A1/A2/O-MBR, citing improved redox control and longer SRTs as critical contributors. Similarly, Zeng *et al.,* [20] achieved 75% TN removal through nitrification–denitrification pathways, reducing the reliance on external carbon sources. In the present study, the lower TN performance may be attributed to a conservative IMLR rate of 100% and fixed anoxic HRT. Nevertheless, since TN is not regulated under Malaysia's DOE discharge standards, the existing configuration remains compliant. The TP removal efficiency of 86.70% in this study was lower compared to the values reported by Wang *et al.,* [18] (91.1% to 93.4%) and Guo *et al.,* [21] (90.53%). Zhao *et al.,* [17] also demonstrated TP removal efficiencies of 89% in an AAO-MBR system, emphasizing the benefits of membrane filtration in achieving higher phosphorus removal. This difference can be attributed to the lower efficiency of the biological phosphorus removal mechanisms in the advanced AAO reactor design. Different HRT of the anaerobic zone will affect the TP removal efficiencies promoting more effective phosphorus uptake and release cycles. Nevertheless, TP discharge limit is still within the effluent discharge standard A of the EQA requirement for stagnant water body. These findings underscore the effectiveness of the advanced

AAO reactor in meeting regulatory standards and optimizing organic matter and nutrient removal from the sewage [1].

Unlike MBR-based AAO systems, which often achieve higher nutrient removal at the expense of elevated energy consumption and maintenance demands, the advanced AAO reactor in this study achieved compliance using a passive, energy-efficient configuration. This supports its application in regions prioritizing low OPEX and carbon footprint.

4. Conclusions

As this is the first implementation of the advanced AAO reactor in Malaysia, the study results demonstrated the outstanding performance in the removal of both organic matters (BOD_5 & COD) and nutrients (AMN, TN and TP). The advanced AAO reactor consistently achieved compliance with effluent discharge requirements, showcasing its effectiveness in meeting stringent regulatory standards. Good removal efficiencies were observed, with BOD_5 and COD removal rates reaching 96.7% and 94.0%, respectively. Similarly, nutrient removal rates for AMN, TN and TP were 83.9%, 64.2% and 86.7%, respectively. The effluent concentrations for organic matter averaged 2.8 ± 1.2 mg/L for BOD_5 and 15.4 ± 6.8 mg/L for COD. For nutrient removal, the effluent concentrations averaged 1.7 ± 1.0 mg/L for AMN, 6.5 ± 2.7 mg/L for TN and 0.5 ± 0.3 mg/L for TP. All these values are well within the permissible limits specified under MSIG Standard A effluent discharge criteria.

Despite variations in the influent sewage characteristics and hydraulic loading during the study period, the advanced AAO reactor demonstrated its robustness and adaptability. One of its key advantages is its ability to operate with a shorter HRT compared to conventional processes which typically demand longer HRTs. This advantage not only could enhance the treatment capacity and capability to remove both TN and TP but also reduces the footprint and operational costs, making the advanced AAO reactor a more efficient and practical choice for modern wastewater treatment in Malaysia. Unlike lab or pilot-scale studies, this evaluation was conducted on a full-scale STP treating actual municipal sewage with real-time load variability, making the findings directly translatable to real-world practice. These findings underscored the advanced AAO reactors' ability to effectively reduce pollutant levels, confirming its reliability and efficiency as a cutting-edge solution for sewage treatment in compliance with Malaysia's regulatory framework for TP removal requirement in the future where the advanced AAO reactor can be one of the recommended processes for biological phosphorus removal method. Future enhancements could include dynamic IMLR adjustment, anaerobic HRT tuning, or integration with AI-driven aeration control to further optimize nutrient removal while maintaining cost-efficiency

Acknowledgement
The authors wish to extend their gratitude to Jabatan Perkhidmatan Pembetungan (JPP) as the project owner and BEWG (M) Sdn. Bhd. as the main contractor for the project.

References

[1] Metcalf and Eddy. *Wastewater Engineering: Treatment and Resource Recovery*. Fifth. 2014.
[2] Department of Environmental Malaysia, "Environmental Quality Report 2020," 2020.
[3] Izadi, Parnian, Parin Izadi, and Ahmed Eldyasti. "Design, operation and technology configurations for enhanced biological phosphorus removal (EBPR) process: a review." *Reviews in Environmental Science and Bio/Technology* 19 (2020): 561-593. https://doi.org/10.1007/s11157-020-09538-w
[4] Xiaolian, Wang, Peng Yongzhen, Wang Shuying, Fan Jie, and Cao Xuemei. "Influence of wastewater composition on nitrogen and phosphorus removal and process control in A 2 O process." *Bioprocess and Biosystems Engineering* 28 (2006): 397-404. https://doi.org/10.1007/s00449-006-0044-5

[5] Chen, Yongzhi, Chengyao Peng, Jianhua Wang, Liu Ye, Liangchang Zhang, and Yongzhen Peng. "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, no. 10 (2011): 5722-5727. https://doi.org/10.1016/j.biortech.2011.02.114
[6] SPAN, *Malaysian Sewerage Industry Guideline - Sewage Treatment Plant*. Third., vol. IV. 2009.
[7] Pham, Quoc Bao, M. S. Gaya, S. I. Abba, R. A. Abdulkadir, Parvaneh Esmaili, Nguyen Thi Thuy Linh, Chetan Sharma et al. "Modeling of Bunus regional sewage treatment plant using machine learning approaches." *Desalination and Water Treatment* 203 (2020): 80-90. https://doi.org/10.5004/dwt.2020.26160
[8] Zhang, M. H., and Y. Huang. "Engineering application of an improved AAO process." In *Journal of Physics: Conference Series*, vol. 2202, no. 1, p. 012051. IOP Publishing, 2022. https://doi.org/10.1088/1742-6596/2202/1/012051
[9] Lei, Shuhan, Jianqiang Zhao, Junkai Zhao, Shuting Xie, Ju Zhang, and Bingfeng Shi. "Optimization of A2O Process by Changing Anoxic Tank Volume Based on GPS-X Simulation." (2022). https://doi.org/10.21203/rs.3.rs-2058607/v1
[10] Fang, Fang, Li-Li Qiao, Jia-Shun Cao, Yi Li, Wen-Ming Xie, Guo-Ping Sheng, and Han-Qing Yu. "Quantitative evaluation of A2O and reversed A2O processes for biological municipal wastewater treatment using a projection pursuit method." *Separation and Purification Technology* 166 (2016): 164-170. https://doi.org/10.1016/j.seppur.2016.04.036
[11] Sakuma, M. "A2O Process Introduced to Seven WWTPs in Regional Sewerage." *Bureau of Sewerage, Tokyo Metropolitan Government* (2005). https://doi.org/10.2175/193864705783867756
[12] Lopes, Carla Limberger, Tatiane Martins de Assis, Fernando Hermes Passig, Adriana Neres de Lima Model, Juliana Bortoli Rodrigues Mees, Francisco J. Cervantes, Jackeline T. Gotardo, and Simone Damasceno Gomes. "Nitrogen removal from poultry slaughterhouse wastewater in anaerobic-anoxic-aerobic combined reactor: Integrated effect of recirculation rate and hydraulic retention time." *Journal of Environmental Management* 303 (2022): 114162. https://doi.org/10.1016/j.jenvman.2021.114162
[13] Diaz, Ruby, Brendan Mackey, Sreeni Chadalavada, Phil Heck, and Ramesh Goel. "Enhanced Bio-P removal: Past, present, and future–A comprehensive review." *Chemosphere* 309 (2022): 136518. https://doi.org/10.1016/j.chemosphere.2022.136518
[14] Vo, Duc-Thuong, Hoang-Vinh-Truong Phan, Le-Thuy-Thuy-Trang Hoang, Van-Kieu Nguyen, Thanh-Nha Tran, and Minh-Trung Dao. "Application of an anaerobic–anoxic–oxic–oxic (AAO/O) model to the treatment of real domestic wastewater." *Journal of Chemistry* 2022, no. 1 (2022): 9456026. https://doi.org/10.1155/2022/9456026
[15] Eghombi, Elvis, Hyunsik Kim, Yang-Hun Choi, Mi-Hwa Baek, Mallikarjuna N. Nadagouda, Pyung-Kyu Park, and Soryong Chae. "Efficient phosphorus recovery from municipal wastewater using enhanced biological phosphorus removal in an anaerobic/anoxic/aerobic membrane bioreactor and magnesium-based pellets." *Membranes* 12, no. 2 (2022): 210. https://doi.org/10.3390/membranes12020210
[16] Li, Fenfen, Xinyue An, Cuimin Feng, Jianwei Kang, Junling Wang, and Hongying Yu. "Research on operation efficiency and membrane fouling of A2/O-MBR in reclaimed water treatment." *Membranes* 9, no. 12 (2019): 172. https://doi.org/10.3390/membranes9120172
[17] Zhao, Wentao, Qian Sui, Xuebing Mei, and Xueting Cheng. "Efficient elimination of sulfonamides by an anaerobic/anoxic/oxic-membrane bioreactor process: Performance and influence of redox condition." *Science of The Total Environment* 633 (2018): 668-676. https://doi.org/10.1016/j.scitotenv.2018.03.207
[18] Guo, Jingbo, Shengming Qiu, Luyu Dai, Lanhe Zhang, Lingwei Meng, Mingwei Liu, and Hong Yao. "The occurrence and removal of steroid estrogens in a full-scale anaerobic/anoxic/aerobic-membrane bioreactor process and the implication of the bacterial community dynamics." *Journal of Environmental Chemical Engineering* 10, no. 2 (2022): 107294. https://doi.org/10.1016/j.jece.2022.107294
[19] Wang, Lin, Bingrong Li, Yongmei Li, and Jianmin Wang. "Enhanced biological nitrogen removal under low dissolved oxygen in an anaerobic-anoxic-oxic system: Kinetics, stoichiometry and microbial community." *Chemosphere* 263 (2021): 128184. https://doi.org/10.1016/j.chemosphere.2020.128184
[20] Zeng, Wei, Lei Li, Yingying Yang, Shuying Wang, and Yongzhen Peng. "Nitritation and denitritation of domestic wastewater using a continuous anaerobic–anoxic–aerobic (A2O) process at ambient temperatures." *Bioresource Technology* 101, no. 21 (2010): 8074-8082. https://doi.org/10.1016/j.biortech.2010.05.098
[21] Wang, Kun, Chuanting Zhou, Hua Zhou, Ming Jiang, Guang Chen, Cong Wang, Zhenjian Zhang, Xiaodan Zhao, Lu-Man Jiang, and Zhen Zhou. "Comparison on biological nutrient removal and microbial community between full-scale anaerobic/anoxic/aerobic process and its upgrading processes." *Bioresource Technology* 374 (2023): 128757. https://doi.org/10.1016/j.biortech.2023.128757