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Integrating Suspended Sludge and Fixed Film into a Biological Wastewater Treatment System to Enhance Nitrogen Removal

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Abstract: Integrated fixed-film activated sludge (IFAS) technology greatly enhances nitrogen removal effectiveness and treatment capacity in municipal wastewater treatment plants, addressing the issue of limited land availability. Hence, this method is appropriate for treating household wastewater from office buildings. The research was conducted at the wastewater treatment plant in an office building in Ho Chi Minh City, Vietnam. Experiments were conducted to ascertain the most favorable working conditions, including hydraulic retention time (HRT), alkalinity dosage, and dissolved oxygen (DO). According to the study, the IFAS system had the highest nitrogen removal effectiveness when operated at a hydraulic retention time (HRT) of 7 h, an alkalinity dose of 7.14 mg$CaCO_3$/mgN-NH_4^+, and a dissolved oxygen (DO) value of 6 mg/L. The nitrification efficiency ranges from 89.2% to 98.8%. The N-NO_3^- concentration post-treatment is within the range of 27–45 mgN-NO_3^-/L, which is lower than the allowable discharge limit of 60 mg/L as per Vietnam's wastewater discharge requirements. The research findings have enhanced the efficiency of the office building management process, thereby promoting the sustainable growth of society.

Keywords: integrated fixed-film activated sludge (IFAS); domestic wastewater; office building; simultaneous nitrification and denitrification (SND)

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Citation: Bui, Q.C.; Phan, N.N.M.; Nguyen, T.V.; Yang, C.-C.; Chen, K.-F.; Tsai, Y.-P. Integrating Suspended Sludge and Fixed Film into a Biological Wastewater Treatment System to Enhance Nitrogen Removal. *Processes* **2024**, *12*, 2131. https://doi.org/10.3390/pr12102131

Academic Editor: Andrea Petrella

Received: 31 August 2024
Revised: 25 September 2024
Accepted: 27 September 2024
Published: 30 September 2024

1. Introduction

The environment is experiencing significant impacts due to the proliferation of office buildings and the continuous growth of society. The degradation of Earth's ecosystems results from altering natural areas caused by urban sprawl. In addition, the release of untreated residential wastewater from office buildings poses a substantial environmental hazard [1]. Consequently, various environmental problems have arisen, including heightened usage of energy and water, as well as the production of pollutants such as chemical oxygen demand (COD), ammonia nitrogen, sulfur dioxide, and nitrogen oxides [2]. Therefore, treating household wastewater from office buildings is considered a crucial activity in sustainable urban development aimed at reducing the environmental consequences of the growing number of office buildings.

Several investigations have consistently found increased nitrogen levels in the wastewater produced by office buildings [3–6]. This matter is highly significant as it has the potential to contaminate groundwater [5] and threaten aquatic environments [6]. Nitrogen compounds can inflict substantial harm on the environment, such as the reduction in oxygen levels in water bodies or the process of eutrophication [7]. Effective treatment methods are necessary to remove these increased nitrogen levels efficiently. Various technologies and strategies have been examined to treat wastewater effectively. Li et al. studied the operational efficiency and membrane fouling of the A2/O-MBR process in reclaimed water treatment [8]. They highlighted the significance of maintaining stable effluent water quality and the role of microbial diversity in effectively removing organics and facilitating the nitrification of ammonia nitrogen. Pedrouso et al. investigated the treatment of digested blackwater in a reactor that uses a partial nitrification–anammox process with alternating periods of starvation and reactivation [9]. Zhang et al. developed a method that combines partial nitrification and denitrification with polishing anammox to remove nitrogen from low-C/N residential wastewater. This approach resulted in a high efficiency of nitrogen removal [10]. Huang et al. devised a method combining partial denitrification with anaerobic ammonium oxidation (anammox) in a continuous flow anoxic/oxic biofilm reactor, significantly increasing nitrogen removal efficiency [11]. In addition, Halicki et al. presented evidence of successfully eliminating nitrogen and phosphorus compounds in household wastewater through natural treatment systems, highlighting the capacity to reduce nutrient levels in wastewater [12]. These studies demonstrate the potential of many techniques to eliminate nitrogen from domestic wastewater efficiently. Nevertheless, every system possesses specific constraints. Given the extensive use of the continuous flow process, it is imperative to examine the efficacy and reliability of the innovative technology before its actual implementation. However, information was scarce, particularly about nitrogen removal's initial and long-term effectiveness in treating real domestic wastewater in office buildings.

The integrated fixed-film activated sludge (IFAS) process has numerous benefits in eliminating nitrogen from wastewater. According to Waqas et al., it has been demonstrated that this method may produce a clearance rate of over 90% for combined chemical oxygen demand and ammonia [13]. Additionally, it improves the settling qualities of sludge and enhances operational stability. The technique also facilitates the simultaneous occurrence of nitrification and denitrification, resulting in reduced amounts of chemical oxygen demand, ammonium nitrate, and total nitrogen in the effluent [14]. Furthermore, the IFAS process can effectively remove nitrogen from sewage, exhibiting impressive nitrogen removal rates [15]. Consequently, the IFAS process is appropriate for implementation in wastewater treatment facilities in office buildings. Nevertheless, the specific elements that influence the efficacy of nitrogen removal in office buildings using this technique are not fully understood.

Therefore, this study assessed the variables that impact the nitrogen removal process in the domestic wastewater of an office building in Vietnam using IFAS technology. The discussion concerns crucial operational factors such as hydraulic retention time (HRT), dissolved oxygen (DO) concentration, and alkali dosage. The results analyze the primary aspects influencing system stability and provide a strategy to guarantee stable operation, contributing to the sustainable development of society.

2. Materials and Methods

2.1. Plant Description

This research was conducted at a domestic wastewater treatment facility in an office building in Ho Chi Minh City, Vietnam. The plant has a daily capacity of 40 m^3/day. Figure 1 displays the diagram of the wastewater treatment process. Following the concentration in the equalization tank, the wastewater is fed into an aerobic tank containing carrier material (Figure 2). After the aerobic interaction between the wastewater and microorganisms, the wastewater flows automatically to an anoxic tank, a secondary clarifier, and a disinfection tank before being injected into the city's public drainage network. The system was consistently functioning without any issues, and the post-treatment pollution components comply with the discharge requirements set by the Vietnamese Government.

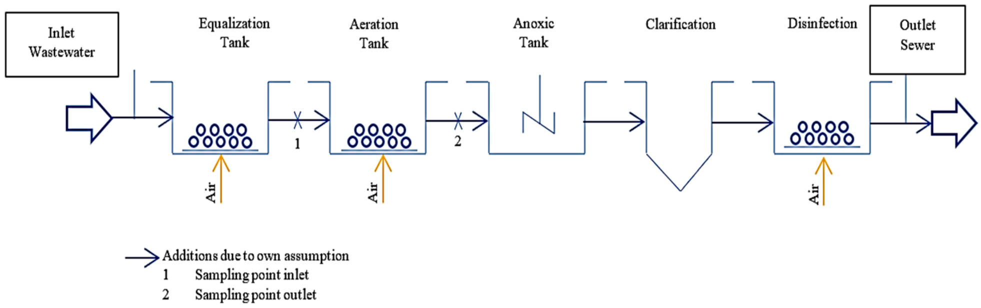

Figure 1. Process flowchart for office building wastewater treatment.

Figure 2. The carrier materials used in the research.

2.2. The Carrier Materials

The carrier materials for this study are constructed using polypropylene (PP), as shown in Figure 2. Polypropylene is chemically stable, corrosion-resistant, stable to acid and alkali, cheap, and of a high strength. The diameter is 105 mm, porosity is 90–92%, specific surface area is 150–180 m^2/m^3, and volume is 23–33 L/m^3.

2.3. Seed Sludge and Domestic Wastewater

The inoculated sludge was obtained from the return ditch of the second settling tank of a domestic wastewater treatment plant, where the sludge maintained a high activity with an SV30 of about 20~30% and a yellowish-brown color. The water for the experiment was obtained from the fine-grating effluent of a domestic wastewater treatment plant at the office building. The quality of the influent water is shown in Table 1.

Table 1. Characteristics of influent wastewater.

Parameters	Unit	Values
pH	-	6.6–7.7
SS	mg/L	34–80
COD	mgO_2/L	144–432
N-organic	mg/L	9–15
$N\text{-}NH_4^+$	mg/L	49–90
$N\text{-}NO_2^-$	mg/L	0.2–8.0
Alkalinity	$mgCaCO_3/L$	160–480

2.4. Factors Affecting Treatment Effectiveness

2.4.1. Hydraulic Retention Time (HRT)

Hydraulic retention time (HRT) is an essential parameter for determining the capacity of a wastewater treatment plant and has significant implications for cost reduction. Reducing the HRT can significantly lower the plant's overall cost, provided the discharge parameters are met. Nevertheless, the choice of HRT will vary depending on the concentration of contaminants in each area [16].

This study was conducted for 11 days, with HRTs of 7 h, 5.8 h, 4.7 h, and 3.9 h, respectively. Each retention time is studied for a duration of three days. The minimum hydraulic retention period is 3.9 h (at a flow rate of 3 m^3/h) and was only investigated for 2 days. When the hydraulic retention time is altered while keeping the total treatment flow the same throughout the day, the result is an increase in the hourly load, while the load during the day and night remains unchanged. The quantity of alkalinity supplement chemicals introduced is 11.5 kg/day, corresponding to an alkalinity consumption of 7.14 $mgCaCO_3/mgN\text{-}NH_4^+$. This amount is sufficient to fully convert the measured quantity of ammonia in the wastewater. The dissolved oxygen concentration is consistently maintained at around 6 mgO_2/L.

2.4.2. Alkalinity

Alkalinity is a critical factor influencing nitrification, where ammonium ($N\text{-}NH_4^+$) is converted to nitrate ($N\text{-}NO_3^-$). Scientists have linked alkalinity to nitrification/denitrification for decades, although little is known about its effect on effluent nitrogen content. The robust association between alkalinity and effluent nitrogen concentration illustrates the potential for utilizing alkalinity as a reliable indicator in nitrification/denitrification processes [17]. The alkalinity requirement is determined based on the bicarbonate needed to counteract the acidity produced during nitrification. Theoretical calculations suggest that an alkalinity consumption of 7.14 $mgCaCO_3/mgN\text{-}NH_4^+$ is enough to convert all the ammonia entering wastewater into nitrate fully [17,18]. Therefore, the amount of alkalinity required to remove ammonia through nitrification can be calculated using the following formula:

$$Alk_{\text{ required}} = N\text{-}NH_4^+{}_{\text{ influent}} \times 7.14 \text{ mg/L alkalinity to nitrify}$$

where $Alk_{\text{ required}}$ is the alkalinity requirement, and mg/L, $N\text{-}NH_4^+{}_{\text{ influent}}$ is the influent (raw) ammonia, mg/L.

This study examined the influence of different amounts of alkaline dosage on the effectiveness of ammonia therapy. The alkaline dosages tested were 7.45 mg of $CaCO_3$/mg of $N\text{-}NH_4^+$, 7.14 mg of $CaCO_3$/mg of $N\text{-}NH_4^+$, and 6.83 mg of $CaCO_3$/mg of $N\text{-}NH_4^+$. The duration of the study is 9 days in total. The DO concentration is 6 mgO_2/L, and the HRT is 7 h.

2.4.3. Dissolved Oxygen (DO)

Dissolved oxygen (DO) is vital to biological nutrient removal (BNR). Traditional nitrification and denitrification require 1–7 mgO_2/L dissolved oxygen (DO). In anoxic–aerobic conditions, the optimal DO demand is 1–4 mgO_2/L compared to 6–7 mgO_2/L in fully aerobic conditions [19].

The investigation was carried out using a hydraulic retention time (HRT) of 7 h and an alkaline intake of 7.14 mg of $CaCO_3$/mg of $N\text{-}NH_4^+$. The study examined three DO levels: 6 mgO_2/L, 4 mgO_2/L, and 2 mgO_2/L. The goal was to identify the optimal DO concentration required to treat the office building's wastewater efficiently.

2.5. Sampling and Analysis

Using a HACH HQ30D multiparameter sensor (HACH Instruments, Loveland, CO, USA), pH and dissolved oxygen were measured on-site and analyzed six times daily (08:00, 10:00, 12:00, 14:00, 16:00, and 18:00) with varying dissolved oxygen values, and four times daily (06:00, 10:00, 14:00, and 18:00) with differing hydraulic retention durations over multiple days. The concentrations of $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ were quantified using a spectrophotometer (APHA 4500 NH_3 G for $N\text{-}NH_4^+$ and EPA 352.1 for $N\text{-}NO_3^-$). Titration was employed to quantify alkalinity (APHA 2320 B) [20].

3. Results

3.1. Effects of HRT on Treatment Efficiency

The impact of hydraulic retention time (HRT) on nitrogen removal efficiency in domestic wastewater treatment has been thoroughly researched. The findings indicate that alterations in HRT have a substantial influence on the effectiveness of different treatment systems. Typically, a longer HRT improves nitrogen removal efficiency by providing sufficient time for crucial microbial processes, such as nitrification and denitrification, to occur more effectively. Studies suggest that prolonging HRT can enhance nitrogen removal efficiencies. Janyasupab and Jampeetong observed that extending HRT to 5 days significantly enhanced nitrate nitrogen ($N\text{-}NO_3^-$) removal, especially in biochar-based systems, due to extended contact time with denitrifying bacteria [21]. Ren et al. noted that extending the hydraulic retention time (HRT) from 4 to 5 h substantially increased the effluent nitrate concentration, indicating insufficient nitrification at lower retention durations [22].

The $N\text{-}NH_4^+$ concentration remained below the permissible discharge level (12 mg/L) throughout the 3-day operation, with treatment efficiency ranging from 85% to 91%. This was achieved with an HRT of 7 h (Q = 1.67 m^3/h, $L_{organic}$ = 0.55–0.88 kg/m^3·day, $L_{ammonia}$ = 0.20–0.29 kg/m^3·day). This finding was analogous to the research by Singh et al. [23]. However, despite a drop in the $N\text{-}NH_4^+$ concentration after treatment, the effectiveness of the $N\text{-}NH_4^+$ treatment does not fulfill the requirements for discharge based on the remaining HRT values. Therefore, it may be inferred that if the hourly operating flow is increased (resulting in a decrease in HRT) beyond the calculated flow rate of 1.67 m^3/h, the treatment efficiency fails to meet the criteria for wastewater disposal. Hence, it is illogical to reduce the duration of daily operations at the treatment station by augmenting the rate of treatment per hour. In addition, the research findings indicate that the treatment process will not yield the intended outcome if there is an increase in the $N\text{-}NH_4^+$ concentration in the incoming wastewater [24–26]. Overloaded treatment systems reduce nutrient removal effectiveness, causing nitrite and ammonia buildup, which harms the environment and humans. Nutrients that are not removed can pollute groundwater and surface water [27].

Figure 3 demonstrated that the combined concentration of $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ in the treated wastewater (31–72 mg/L) is lower than the influent wastewater's $N\text{-}NH_4^+$ concentration (57–93 mg/L). As a result, nitrification and denitrification occurred simultaneously in the aerobic-activated sludge tank [28]. This is very suitable for wastewater treatment systems in urban areas with limited land [29]. In addition, the simultaneous occurrence of these two processes also significantly affects other parameters in the treated wastewater [30]. Nitrification requires high dissolved oxygen and reduces pH by forming nitric acid, while denitrification increases pH [31]. Nitrification reduces ammonia concentrations, but it can lead to nitrite accumulation if not complete [32]. If denitrification fails, nitrates will accumulate and harm the ecosystem [33]. Denitrification reduces COD and BOD by using organic material as a substrate [34]. HRT must be optimized to provide adequate time for both processes and adjust aerobic and anoxic oxygen concentrations to avoid hindering either process. Nevertheless, when the operating flow (reducing HRT) is increased, the contact time between denitrifying and nitrate-reducing bacteria decreases, and high nitrite accumulation inhibits the denitrification process. Consequently, the efficiency of the nitrate reduction process also decreases with the operating stages. Additionally, lack of nutrient control increases operating costs due to the need for more chemicals and energy. It is crucial to effectively control nutrient loading rates to prevent system overload or inhibition [35]. This can be regulated by optimizing the tank dimensions and redesigning the aerobic and anoxic zones to enable HRT modification.

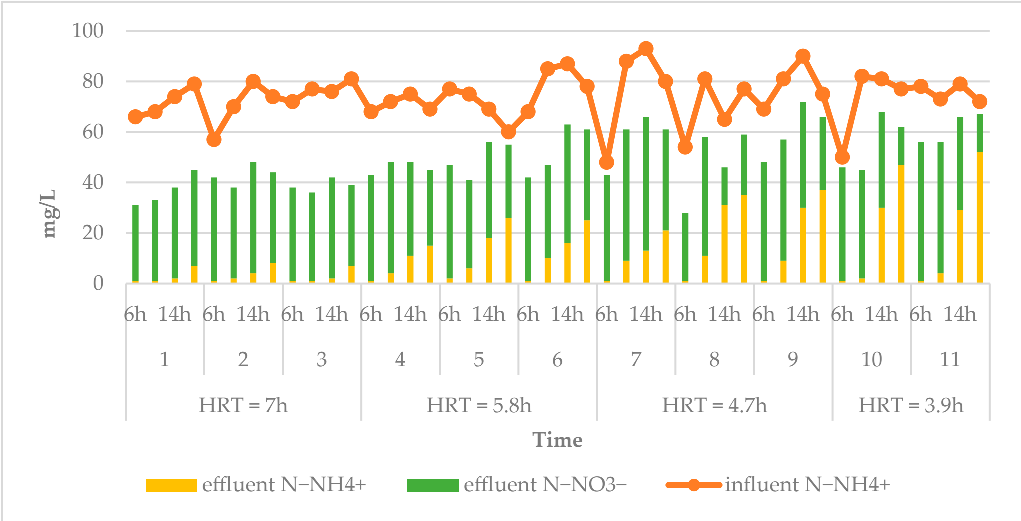

Figure 3. Process denitrification effectiveness for various hydraulic retention times.

3.2. Effect of Alkalinity on Treatment Efficiency

Variations in influent ammonia content directly affect wastewater treatment system alkalinity demand, as the nitrification process uses considerable alkalinity to neutralize the acid created during ammonia to nitrate conversion [36]. An increased ammonia concentration leads to increased H^+ generation, lowering alkalinity and pH, necessitating alkalinity supplementation to maintain appropriate pH for nitrifying bacteria [37,38]. Conversely, low ammonia concentrations deprive nitrifying bacteria of substrate, limiting nitrogen removal efficiency [39]. As hydrogen ion generation decreases with ammonia concentration, alkalinity replenishment decreases.

Numerous nitrogen-eliminating biological and chemical processes necessitate alkalinity, particularly biological nitrogen removal (BNR) systems. Yang et al. illustrated that adding bicarbonate (HCO_3^-) significantly improved nitrogen removal rates in an anammox process, increasing from 5.2 to 11.8 kg of nitrogen removed per day with sufficient alkalinity enhancement [40]. Similarly, Hu et al. found that alkalinity was substantially correlated with the treatment success of the MBR system. Enhancing alkalinity may improve the removal rate of COD and ammonia nitrogen [41]. Furthermore, Ji et al. highlighted that a synergistic approach combining partial denitrification and anammox processes achieved a nitrogen removal efficiency of 95.6% under optimal alkalinity conditions, showcasing the importance of maintaining appropriate alkalinity levels for maximizing nitrogen removal [42].

Figure 4 demonstrates that the ammonia in the wastewater is virtually entirely eliminated if the amount of alkalinity ($NaHCO_3$) is 7.45 $mgCaCO_3/mgN\text{-}NH_4^+$ and 7.14 $mgCaCO_3/mgN\text{-}NH_4^+$. $N\text{-}NH_4^+$ conversion to $N\text{-}NO_3^-$ efficiency declines over time and fails to meet the discharge standards for an alkaline consumption of 6.83 $mgCaCO_3/mgN\text{-}NH_4^+$ ($N\text{-}NH_4^+$ effluent = 12–31 mg/L). Therefore, the calculated alkalinity dose must be added to convert $N\text{-}NH_4^+$ into $N\text{-}NO_3^-$. In addition, adding additional alkalinity is unnecessary because the treatment efficiency is the same, and the leftover $N\text{-}NH_4^+$ content is still below the discharge standard. Moreover, oxygen concentration, pH, retention time, influent water loading, and nitrifying bacteria supplementation must be optimized to consistently remove ammonia under reduced conversion efficiency.

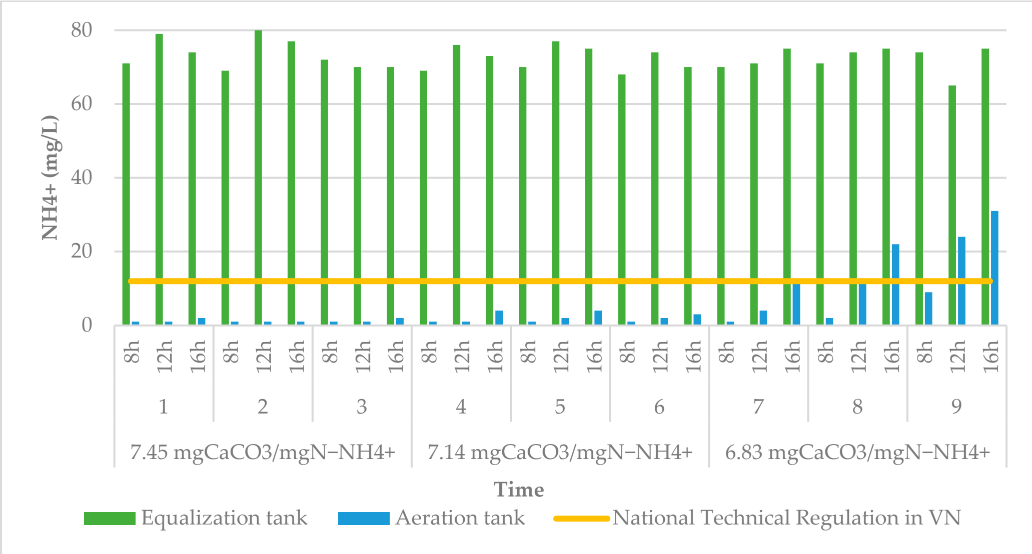

Figure 4. The effectiveness of the nitrification process at various alkali dosage values.

3.3. Effect of DO on Treatment Efficiency

A DO concentration above 6 mg/L can dramatically affect nitrification by suppressing specific bacteria populations in this metabolic reaction. Nitrification is a two-step aerobic process in which ammonia-oxidizing bacteria (AOB) oxidize ammonia to nitrite and then nitrite to nitrate. Oxygen levels affect these microbial processes; therefore, high DO can disturb them. Because high oxygen concentrations reduce denitrifying enzyme activity, nitrogen removal is impeded [43]. Additionally, elevated DO levels influence nitrifying bacterial community dynamics. AOB may outcompete NOB in high DO conditions, causing partial nitrification, where nitrite accumulates instead of being totally oxidized to nitrate [44,45]. In addition, maintaining high DO concentrations for long periods of time will consume a lot of electrical energy, which will affect the cost of wastewater treatment. Due to nitrification processes, low DO levels might suppress the activity of nitrite-oxidizing bacteria (NOB), increasing the nitrite content. Numerous studies have reported this occurrence, which suggests that the metabolic pathways prefer nitrite buildup over nitrate (NO_3^-) accumulation when oxygen levels are low [46]. Furthermore, in aquatic settings, nitrite buildup can also upset microbial communities. The growth of denitrifying bacteria may be impeded in low-oxygen settings because nitrite and its reactive nitrogen species, like nitric oxide (NO), have dangerous properties [47]. Enhancing dissolved oxygen concentrations in process zones improves nitrogen removal [48,49]. Some studies suggest that nitrification can still be effective at DO concentrations as low as 0.3 mg/L to 0.7 mg/L, particularly in systems designed for simultaneous nitrification–denitrification (SND). Jiménez et al. found that maintaining DO levels within this range maximized SND activity, although it also increased susceptibility to sludge bulking [30]. Therefore, optimizing dissolved oxygen levels in treatment systems is crucial for balancing nitrification and denitrification processes. Zhou et al. performed a comprehensive investigation in an Orbal oxidation ditch, demonstrating that nitrogen removal effectiveness was significantly contingent upon the extent of nitrification and denitrification, which were, in turn, affected by the aeration tactics utilized [50].

Figure 5 indicates that the higher the dissolved oxygen concentration, the more efficient the nitrification process. If the DO concentration is around 6 mgO_2/L, the ammonia content after treatment is less than the permitted discharge level. Zhang et al. [51] examined the variations in the concentrations of NH_4^+, NO_2^-, and NO_3^- in the reactor under varied levels of cathodic DO. The findings indicated that N-NH_4^+ removal and nitrification activity exhibited an increase in correlation with increasing DO concentrations. In addition, Lei et al. [52] demonstrated that a low DO level can effectively suppress the proliferation of nitrite-oxidizing bacteria (NOB), resulting in nitrite accumulation. Simultaneously, when the DO concentration is low, the conversion rate of ammoniacal nitrogen is comparatively sluggish.

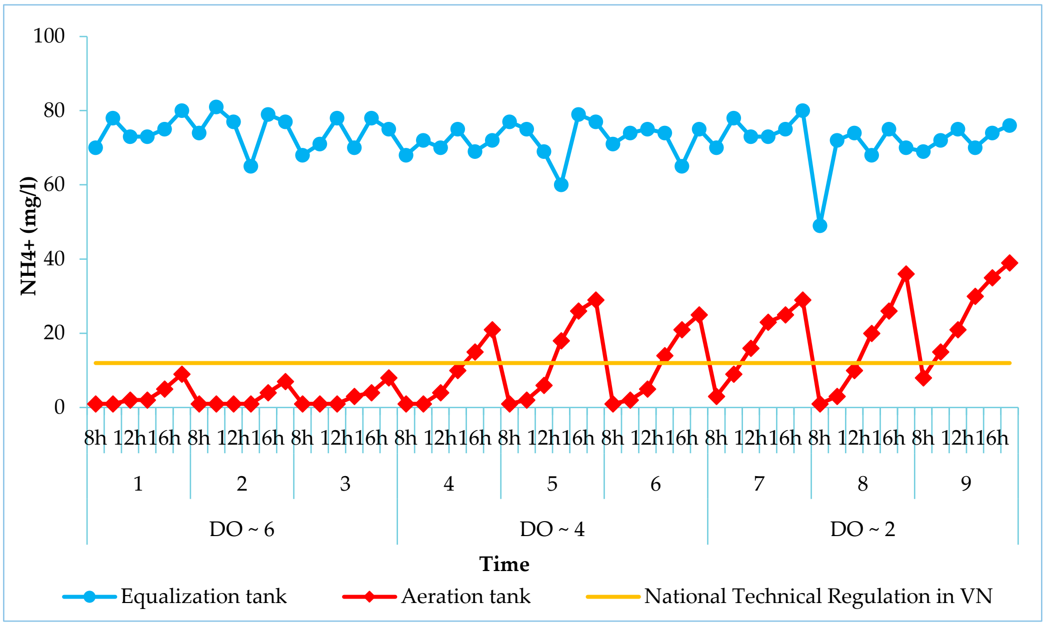

Figure 5. The effectiveness of the nitrification process at various DO values.

When the DO level was below 6 mgO_2/L, the ammonia concentration post-treatment from 8:00 to 12:00 was less than that from 14:00 to 18:00. This outcome occurs because, after 19:00, the wastewater produced by the office building is nearly insignificant, resulting in prolonged retention of the wastewater in the aerobic activated sludge tank. Simultaneously, the nitrification process persists, leading to a significantly reduced ammonia concentration in samples collected during the morning hours of the subsequent day compared to those obtained in the afternoon and evening of the same day.

Optimizing wastewater treatment systems' simultaneous nitrification and denitrification (SND) processes requires biofilms' aerobic–anoxic balance. Several factors influence this balance, including dissolved oxygen (DO) concentration [53,54], the chemical-oxygen-demand-to-nitrogen (COD:N) ratio [55,56], biofilm thickness [57], and operational conditions such as hydraulic retention time (HRT). Suspended sludge and attached biofilm work together to remove organic carbon and improve biological nitrogen removal (BNR) in the IFAS system [58]. IFAS biofilms with a unique multi-layer structure form aerobic and anoxic zones to achieve simultaneous nitrification and denitrification (SND) by coexisting nitrifiers and denitrifiers [13]. SND, which involves microbiological processes of nitrification and denitrification in the same reactor, is promising for BNR [59]. Biofilm microorganisms are layered along DO concentrations. Nitrifying bacteria, which need oxygen for metabolism, live in biofilm's upper layers where DO is higher. Denitrifying bacteria, which thrive in anoxic circumstances, live deeper in the biofilm. This stratification allows both groups to cohabit, enabling SND [60]. Gu et al. found that IFAS systems could remove 73% of influent ammonia shock loads, showing a robust capacity for high ammonia levels [61]. Since biofilm provides a stable home for nitrifying bacteria, IFAS systems may oxidize ammonia better than conventional systems. However, suboptimal carbon sources [62], operational characteristics like DO levels and F:M ratios [63], and microbial community dynamics [64] might reduce denitrification efficiency in IFAS systems. The concurrent optimization of nitrification and denitrification can be accomplished through advanced bioreactor designs [65], the precise regulation of environmental parameters [66], and the application of specific microbial communities [67]. These strategies improve nitrogen removal efficiency and promote sustainable wastewater treatment practices.

It can be seen in Figure 6 that denitrification always occurs because the total concentration of N-NH_4^+ and N-NO_3^- after treatment (32–49 mg/L) is always smaller than the influent N-NH_4^+ concentration (68–80 mg/L). Additionally, DO is maintained at about 2 mg/L, and the N-NO_3^- reduction efficiency is better than that of the other two stages. High yields of SND have been demonstrated by Xia et al. [68] and Machat et al. [58] when dissolved oxygen concentrations are kept between 1 and 2 mgO_2/L. Maintaining a high dissolved oxygen concentration in the fixed-growth aerobic-activated sludge tank does not considerably impact the denitrification process. During the study period, the N-NO_3^- concentration after treatment (9–45 mgN-NO_3^-/L) is lower than the discharge requirement (60 mgN-NO_3^-/L). A dissolved oxygen content of roughly 6 mg O_2/L is required for adequate N-NH_4^+ removal (the post-treatment N-NH_4^+ and N-NO_3^- concentrations do not exceed the prescribed threshold). According to Sriwiriyarat et al. [69], a DO concentration of 6 mgO_2/L was required for SND to maintain efficient nitrification and supply extra nitrous oxides for denitrification in IFAS.

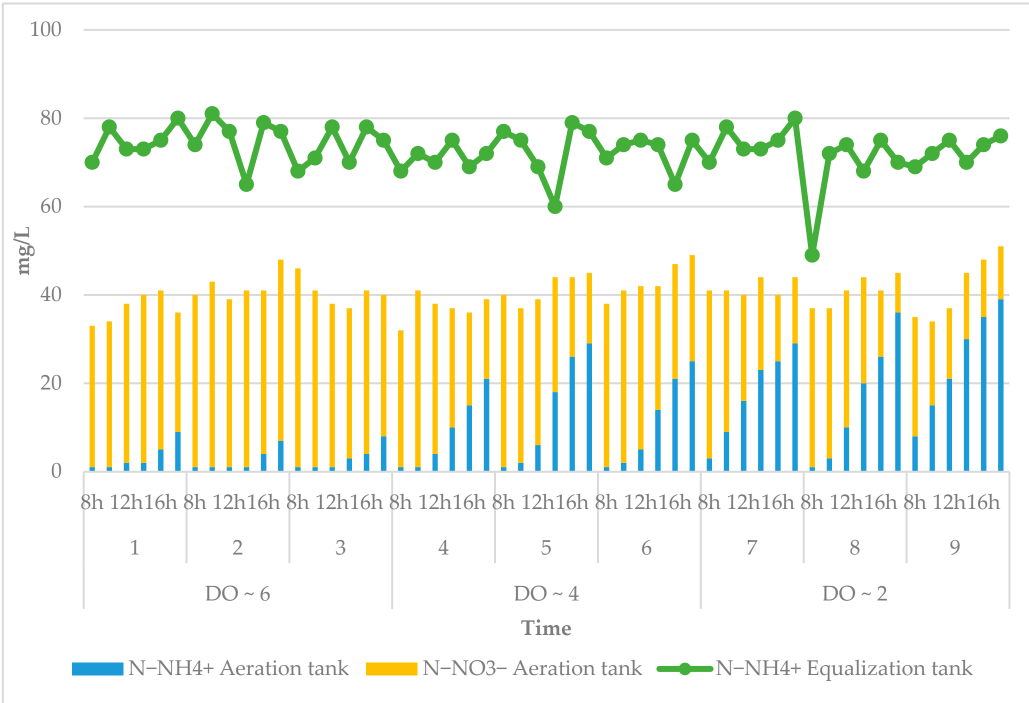

Figure 6. The effectiveness of the denitrification process at various DO values.

4. Conclusions

In this study, we highlighted the effect of important operating parameters, including hydraulic retention time (HRT), alkalinity, and dissolved oxygen (DO) concentration, by proving the efficiency of the integrated fixed-film activated sludge (IFAS) system for nitrogen removal in a domestic wastewater treatment plant for an office building. With post-treatment nitrate (N-NO_3^-) concentrations between 27 and 45 mg N-NO_3^-/L, well below the discharge limit of 60 mg N-NO_3^-/L, optimal conditions, including an HRT of 7 h, an alkalinity dose of 7.14 mg $CaCO_3$/mgN-NH_4^+, and a DO concentration of 6 mgO_2/L, resulted in nitrification efficiencies ranging from 89.2% to 98.8%. By use of suspended sludge, biofilm carriers, and controlled DO levels, simultaneous nitrification and denitrification was encouraged, generating microenvironments for both aerobic and anoxic reactions within the reactor. The alkalinity supplied necessary buffering for the nitrification process, hence preserving pH stability and improving nitrogen removal effectiveness. By optimizing treatment techniques and lowering environmental effects, our results not only support sustainable urban growth but also help urban wastewater management be more cost-effective.

Author Contributions: Q.C.B., N.N.M.P., T.V.N., C.-C.Y., K.-F.C. and Y.-P.T.; methodology: Q.C.B., T.V.N. and Y.-P.T.; investigation: Q.C.B., N.N.M.P. and T.V.N.; formal analysis: T.V.N. and Y.-P.T.; writing—original draft preparation: Q.C.B., N.N.M.P., T.V.N. and Y.-P.T.; writing—review and editing, Q.C.B., T.V.N. and Y.-P.T.; visualization, Q.C.B., T.V.N. and Y.-P.T.; supervision, C.-C.Y. and K.-F.C.; project administration: Q.C.B., T.V.N. and Y.-P.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science and Technology Council, Taiwan, grant number 112-2221-E-260-002-MY3.

Data Availability Statement: Data are available from the authors upon reasonable request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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