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Improving Nitrogen Removal Efficiency in SBR Reactors by Controlling Operational Phases

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Abstract: Wastewater treatment facilities using the activated sludge process are the most widely used solutions worldwide, regardless of the region. According to statistics, the most common option for Vietnam's conditions is the sequenced batch reactor, which is used at a third of wastewater treatment plants (WWTP). Thus, studies of treatment processes in SBRs that seek high-quality treatment may have a wide range of further applications in practice. Another reason is that wastewater treated to meet Vietnamese standards has a significant negative impact on water resources. The research was carried out in relation to Hoaxuan wastewater treatment plants, where pilot models were installed that worked on influent wastewater. Studies of the nitrification process in SBRs (cycle duration 4 h) have shown that the highest efficiency of removal of pollutants (organic pollution by 90%, ammonium nitrogen by 80%) is achieved at a pH value close to 8.0. The increase in pH also had a positive effect on the increase in the specific rate of nitrification. At the second stage of the research, the process of denitrification in SBRs (cycle duration of 6.5 h) was considered. The results demonstrated that treatment quality corresponded to the standards for the Russian Federation, which are stricter than Vietnamese standards (3.0 mg/L vs. 30 mg/L of biochemical oxygen demand; 0.4 mg/L vs. 5 mg/L of ammonium nitrogen). For the second part of the study, a specific denitrification rate was determined in order to establish its dependence on the main parameters of the SBR model performance.

Keywords: wastewater treatment; activated sludge process; sequenced batch reactor; nitrification; denitrification

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1. Introduction

The activated sludge process (ASP) is a method used worldwide for biological treatment of municipal and industrial wastewater [1,2]. ASP is normally held in the activated sludge reactors (ASR). Their simplest version aims at the removal of biodegradable organic matter and organic nitrogen-containing matter by converting ammonia to nitrate under aerobic conditions [3–6]. However, enhanced treatment (e.g., nitrate removal) requires more sophisticated technologies. According to the report of the United States Environmental Protection Agency (USEPA), ASRs are relatively small and require less space than other technologies. However, ASRs may require significant operation costs due to the higher energy demand needed to run the aeration system [7–10]. The effectiveness of the ASP can be impacted by elevated levels of toxic compounds in wastewater that require an industrial pretreatment program to control complex industrial chemicals.

On the other hand, the limitation of conventional ASPs is the enhanced removal of nutrients. Enhanced removal refers to the simultaneous removal of only 5 mg of nitrogen and 1 mg of phosphorus per 100 mg of organic matter, which is usually expressed as a biological oxygen demand (BOD) or chemical oxygen demand (COD). In the conventional

aerobic process, the mass of nutrients removed in 100 mg of activated sludge was 2.3 mg of phosphorus and 12.2 mg of nitrogen [2,11]. Therefore, the removal of nutrients at wastewater treatment plants (WWTPs) is a major challenge because of public health and economic concerns [12–14]. In the biological wastewater process with activated sludge, ammonia removal is accomplished through nitrifying bacteria, which oxidize ammonia to nitrite and then to nitrate. After that, denitrifying bacteria reduce nitrate to gaseous nitrogen through heterotrophic microorganisms [11,15]. Through the nitrogen cycle in nature, denitrification can take place in terrestrial or marine ecosystems. However, ASP denitrification occurs in anoxic conditions, which means the presence of nitrate and the absence of dissolved oxygen. Biological nitrogen removal in wastewater treatment systems and its control reactions are shown in Figure 1. However, a number of barriers may influence forward progress in implementing nutrient removal processes and achieving reductions in aquatic ecosystems, including costs, limitations on physical expansion, and advanced operations and control.

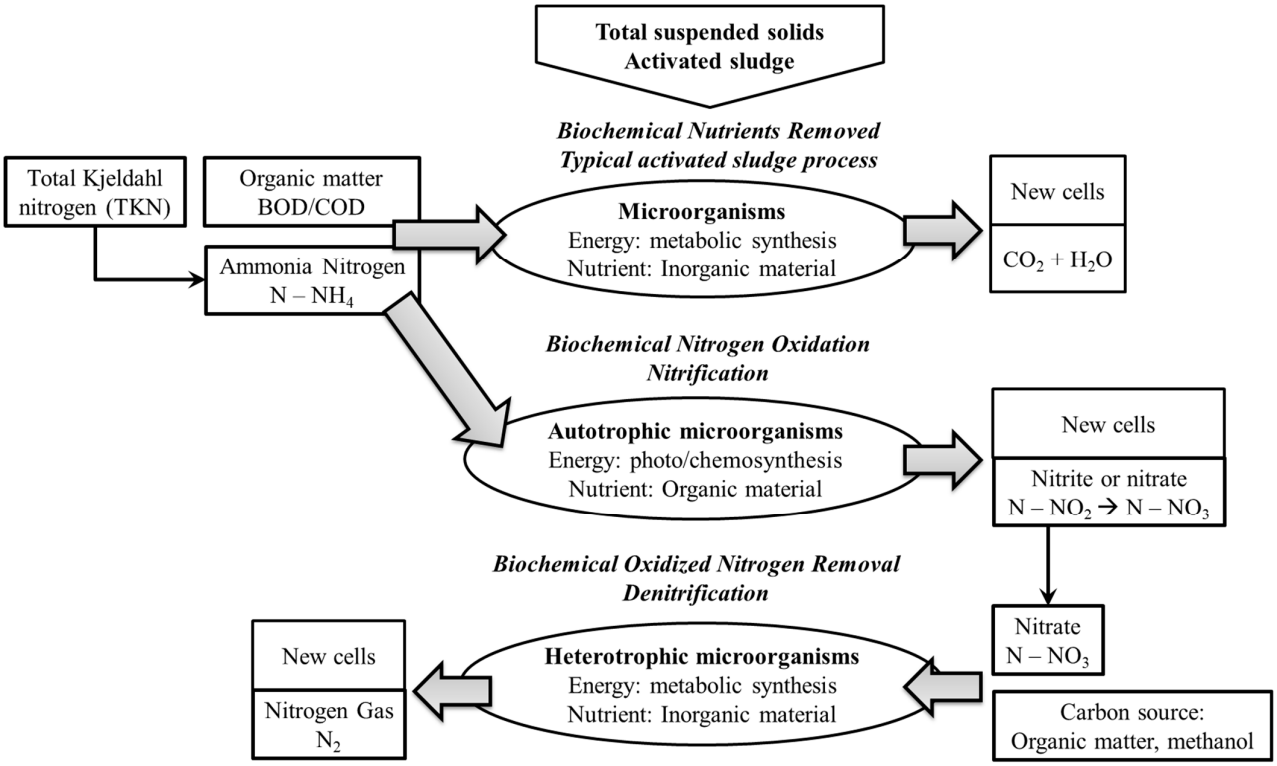


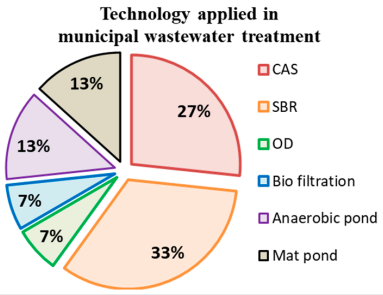
Figure 1. The mechanism of nitrogen transformation within activated sludge process at wastewater treatment plants.

In urban areas, the production of waste from human activities added to the water during its communal use will end up as municipal wastewater [13–16]. Especially in developing countries with combined sewerage systems, human waste, together with the water used for flushing toilets, has been mixed with rainwater and industrial wastewater in local areas before being treated in municipal WWTPs [17]. Due to the frequent use of septic tanks in households, there is a decrease in available carbon for heterotrophic denitrification [18]. Table 1 demonstrates the urban wastewater and sanitation management activities in Vietnam, which is a typical developing country with combined sewerage systems [19,20].

According to the overview of urban sanitation in Table 1, ASRs have been widely applied in municipal WWTPs. Based on the limitations and disadvantages of this technology, the Vietnamese discharge standard [21] regulates the concentration of nutrients in treated wastewater, especially ammonia and nitrates; these should not be higher than 5 mg/L or 30 mg/L, respectively. However, when compared with the Russian standard for

treated wastewater, the amount of nitrogen released into the environment in Vietnam is unacceptable and leads to damage to the environment [22].

Table 1. Vietnamese combine sewerage system and technology municipal wastewater treatment.



Parameter	Vietnamese Standard	Russian Standard
BOD_5 [mg/L]	30	2.1
COD [mg/L]	75	30
$N–NH_4$ [mg/L]	5.00	0.4
$N–NO_3$ [mg/L]	30	9.0

Note: CAS—conventional activated sludge treatment; SBR—sequenced batch reactor; OD—oxidation ditch.

As far as environmental improvement and creating sustainable development in Vietnam and other developing countries are concerned, current research focuses on the assessment of biological nitrogen removal in ASRs through nitrification and denitrification processes and based on local conditions. The aim of the research was to determine the operation parameters of ASRs and to improve the efficiency of pollutants (especially nitrogen) removal in WWTPs by providing high-quality discharge standards. If the required treatment quality is reached, it may allow treated wastewater to be reused for irrigation or agricultural use, supporting environmental restoration [23–25].

2. Materials and Methods

2.1. Overall Approach of the Process and Study Area

The idea of upgrading municipal WWTPs in Vietnam was first mentioned in the Vietnam Urban Wastewater Review in Report No. ACS7712 of the World Bank. The purpose of the study is to increase the efficiency of nitrogen removal in ASRs, which is primarily associated with the optimization of operating conditions [19,20].

The study was carried out on the municipal WWTP "Hoaxuan", which collects and treats municipal wastewater from two main districts of Danang City, the third-largest city in Vietnam. WWTP "Hoaxuan" accepts municipal wastewater from an area with a population of more than 180,000 people and an average flowrate in the dry season of more than 25,000 m^3/d. Figure 2 shows the location of WWTP "Hoaxuan" in Danang City. Figure 3 and Table 2 describe its operation in 2018 [26].



Figure 2. The location of Hoaxuan WWTP in Danang city.

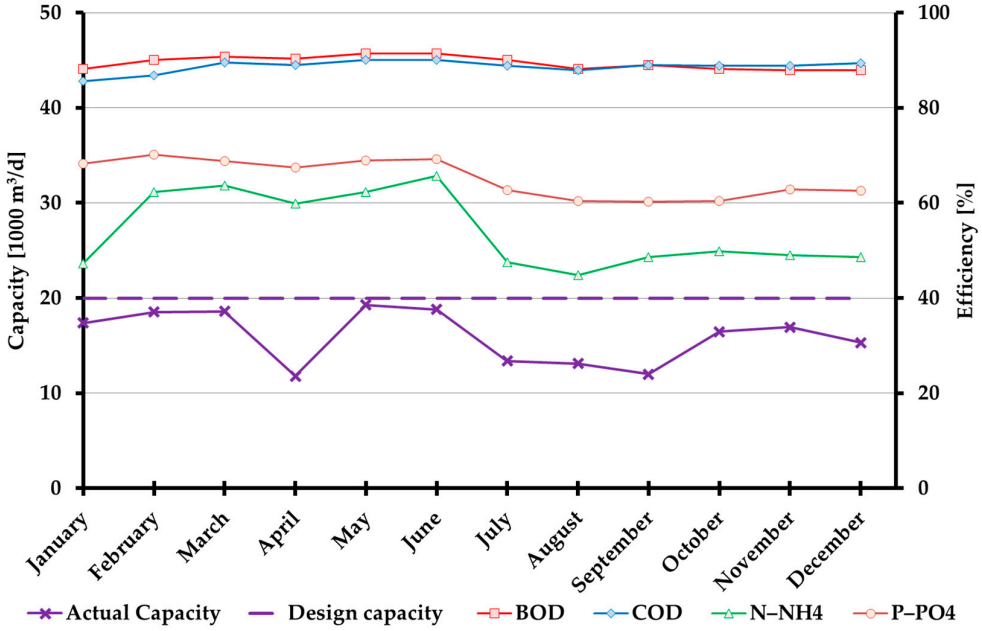


Figure 3. Operation of WWTP "Hoaxuan" in 2018.

Table 2. Operation parameters of WWTP "Hoaxuan" in 2018.

Parameter	Influent	Effluent	Discharge Standard
BOD [mg/L]	53–96	6.32–10.42	30
COD [mg/L]	84–125	11.27–13.20	50
N–NH_4 [mg/L]	10.86–18.65	5.73–9.41	5.0
N–NO_3 [mg/L]	0.18–0.74	17–23	30
P–PO_4 [mg/L]	2.48–4.54	0.93–1.42	6.0

Table 2 shows that BOD_5 and COD concentrations in treated wastewater are lower than the Vietnamese discharge standard. However, the nitrogen concentrations, especially ammonia and nitrate, in treated wastewater exceed the required values. Moreover, the efficiency of the nitrogen removal ranged from 45 to 60%. Therefore, the municipal wastewater that comes to WWTP "Hoaxuan" and the sequenced batch reactor (SBR, the modern variation of an ASR) were the initial data within the experiment used to perform biological nitrogen removal for upgrading WWTPs in Vietnam [27–29].

2.2. Characteristics and Installation of Lab-Scale Model

Modeling is an inherent part of the design of a wastewater treatment system. At the fundamental level, a lab-scale model reduces the complexity of the system and demonstrates the conceptual image of how it functions. From the physical model, which incorporates a statistical approach to mimic, the results of the experiment have been determined. In this way, many potentially feasible solutions may be evaluated quickly and inexpensively, thereby allowing more promising ones to be selected for practical use in the SBR reactor of a municipal WWTP.

A lab-scale SBR (Figure 4) that accepts municipal wastewater from WWTP "Hoaxuan" has been assembled in the laboratory of the Environment Protect Research Centre, Danang University. The model of the SBR reactor was also equipped with mixers, sensors, electrical valves, and pumps. The entire bench was operated and controlled automatically by a computer program. The block scheme of the bench is presented in Figure 5 [23,24].

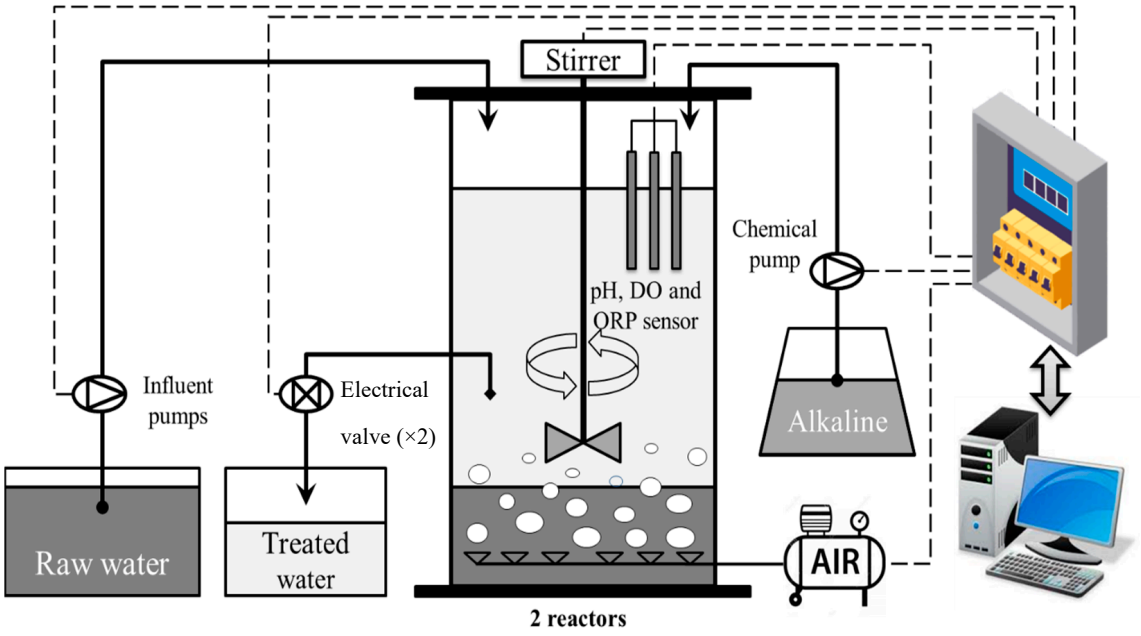


Figure 4. Layout scheme of SBR pilot model.

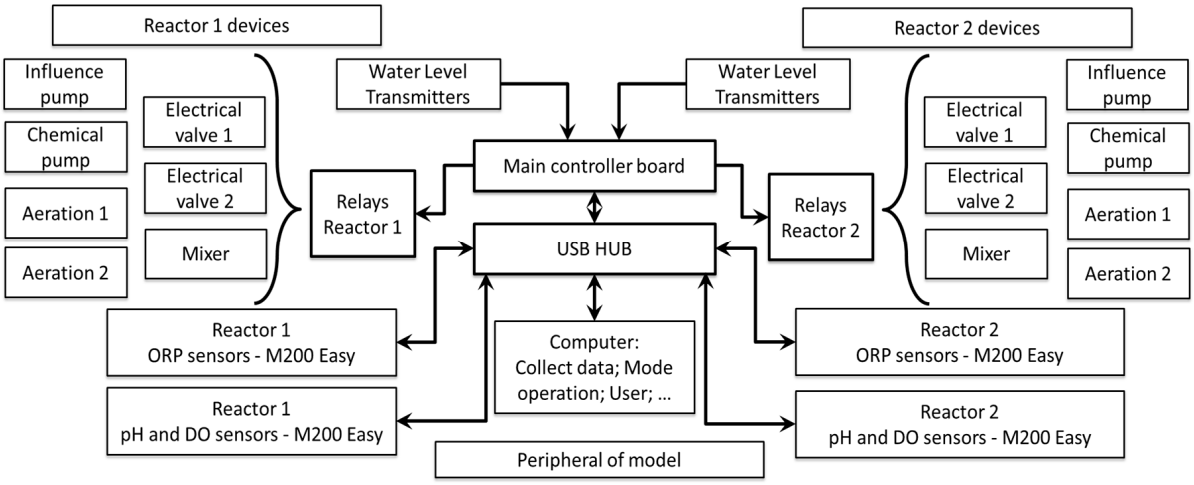


Figure 5. Block scheme of SBR pilot model.

2.3. Experiment Methods

The experiment has been divided into two steps, corresponding to biological reactions (nitrification and denitrification) and to two discharge standards for treated wastewater (Vietnam and Russia). The bench consisted of two SBRs that operated in parallel under continuous-flow conditions for one month; this guarantees the processes of nitrification and denitrification in each reactor. The experiment plot and the mission of each reactor are shown in Figure 6.

The first lab-scale SBR was focused on nitrification and its optimization via the alkalinity and pH, respectively. The main mission of this step of the experiment was to determine the efficiency of ammonia removal through the control of the pH value of the reactor. In addition, the quality of treated wastewater should meet the Vietnamese discharge standard. The major challenge of the second reactor was the evaluation of biological nitrogen removal from municipal wastewater with low-source carbon. Due to the anoxic environment in the reactor, denitrification has occurred for treating municipal wastewater. The Russian discharge standard has been used in the second step of the experiment [30–33].

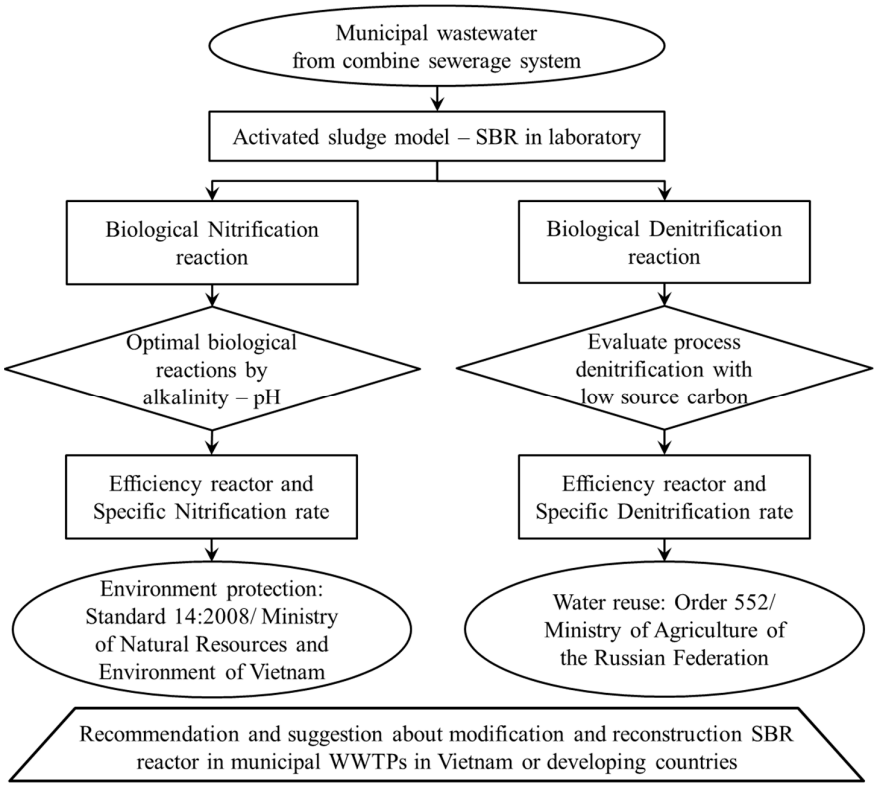


Figure 6. The experiment site and purpose of research.

The purpose of the experiment steps was to determine the specific rates of nitrification (SNR) or denitrification (SDNR), respectively, and the efficiency of nitrogen removal in the SBR reactor. The values of these parameters were obtained after the analysis of influent and effluent samples and mixed liquor in the reactor over time. The following analytical parameters were measured [34,35]:

- BOD, COD, ammonia (N–NH_4), nitrite (N–NO_2), nitrate (N–NO_3), organic nitrogen (N_{org}), hourly influent and effluent analysis per cycle of the reactor operation;
- Temperature, pH, dissolved oxygen (DO), and redox potential (ORP) were fixed by sensors and collected by computer;
- Activated sludge: mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) in biological reactor were analyzed at the beginning and end of SBR circle operation.

According to the analysis results, the performance and organic loading of the reactor have been determined. SNR and SDNR were measured based on the changes in the concentration of nitrogen components (ammonia, nitrite, or nitrate) in the influent and effluent wastewater (Equations (1) and (2)). In the ASP, these rates characterize the growth of nitrate-oxidizing and reducing bacteria [1,2,11,36]:

- SNR:

$$r_N = \left(\frac{\mu_{Nm} \times N}{K_N + N}\right)\left(\frac{K_O}{K_O - DO}\right) - k_{dN} \quad (1)$$

- SDNR:

$$r_{DEN} = -r_{su}\left(\frac{NO_3}{NO_3 + K_{NO_3}}\right)\left(\frac{K'_O}{K'_O + DO}\right)\eta \quad (2)$$

μ_{Nm} is the maximum specific growth rate of nitrifying bacteria [g N_{ox}/g VSS d^{-1}];
N is the nitrogen concentration [mg/L];

K_N is the halved velocity constant; substrate concentration at one-half the maximum specific substrate utilization rate [mg/L];

k_{dN} is the endogenous decay coefficient for nitrifying organisms [g VSS/g VSS/d];

K_O is half-saturation coefficient for DO [mg/L];

DO is the dissolved oxygen concentration [mg/L];

K'_O is the DO inhibition coefficient for nitrate reduction [mg/L];

K_{NO3} is half-velocity coefficient for nitrate limited reaction [mg/L];

r_{DEN} is the maximum specific growth rate of denitrifying bacteria [g N_{red}/g sludge d^{-1}];

r_{su} is the rate of substrate concentration changes due to utilization [g/m^3 d^{-1}];

η is the fraction of denitrifying bacteria in the biomass [g VSS/g VSS].

Through the simulation of nitrogen removal in the SBR, the SNR and SDNR have been calculated and compared with the typical values in the kinetic theory of the ASP. The practical interest of the experiment was to prove the applicability of the nitrogen removal process to the operation and upgrading of biological reactors in municipal WWTPs [37].

3. Results and Discussion

3.1. The First Step of Experiment—Biological Nitrification

The optimization for biological nitrification via alkalinity and pH has been performed in the first step of the experiment. The pH value of the mixed liquid has been controlled and increased gradually to levels of 7.0, 7.2, 7.4, 7.6, and 7.8, respectively. At each pH level, the lab-scale SBR reactor operated for eight cycles (two cycles of warmup and no sampling). The duration of each phase within one operation circle was as follows:

- Filling time: 12 min
- Nitrification phase: 3.0 h
- Settling: 30 min.
- Discharge: 15 min.
- Filling rate: 30% volume of reactor (conventional value in Vietnamese WWTP).

Sampling results demonstrate a decrease in the concentration of pollutants in SBR and their characteristic functions (Figures 7–11).

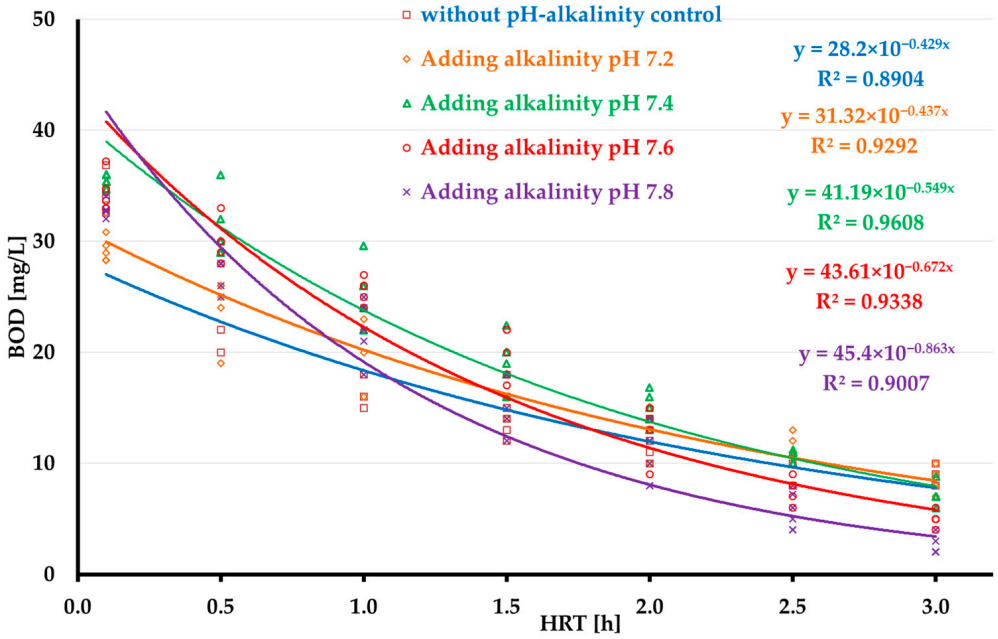


Figure 7. The BOD concentration in influent and effluent of model SBR under various pH conditions.

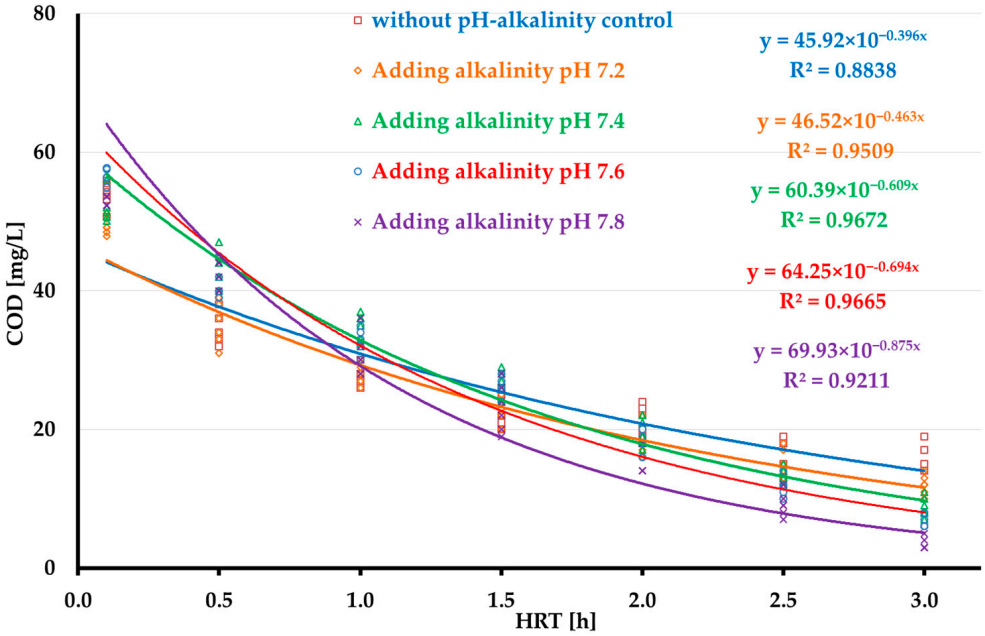


Figure 8. The COD concentration in influent and effluent of model SBR under various pH conditions.

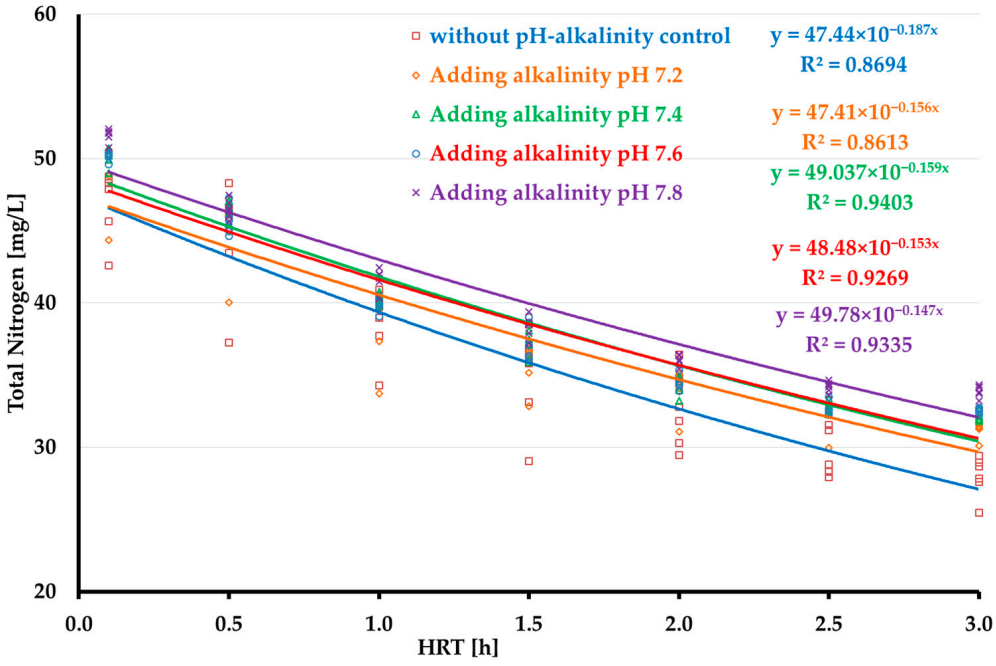


Figure 9. The total nitrogen (TN) concentration in influent and effluent of model SBR under various pH conditions.

Nitrification is carried out by autotrophic bacteria that use inorganic materials as a source of nutrients and photosynthesis or chemosynthesis as a source of energy.

Therefore, organic matter removal has been related to the amount of alkalinity used to intensify nitrification in ASRs. Based on the concentrations of BOD and COD in effluent wastewater and MLSS in the reactor, the reduction of organic matter could be divided into two groups. The first group included biological reactions with a pH value of 7.2. However, the effectiveness of nitrogen removal only increased by 3–5%, and the concentration of ammonia in treated wastewater was reduced by 1–2 mg/L.

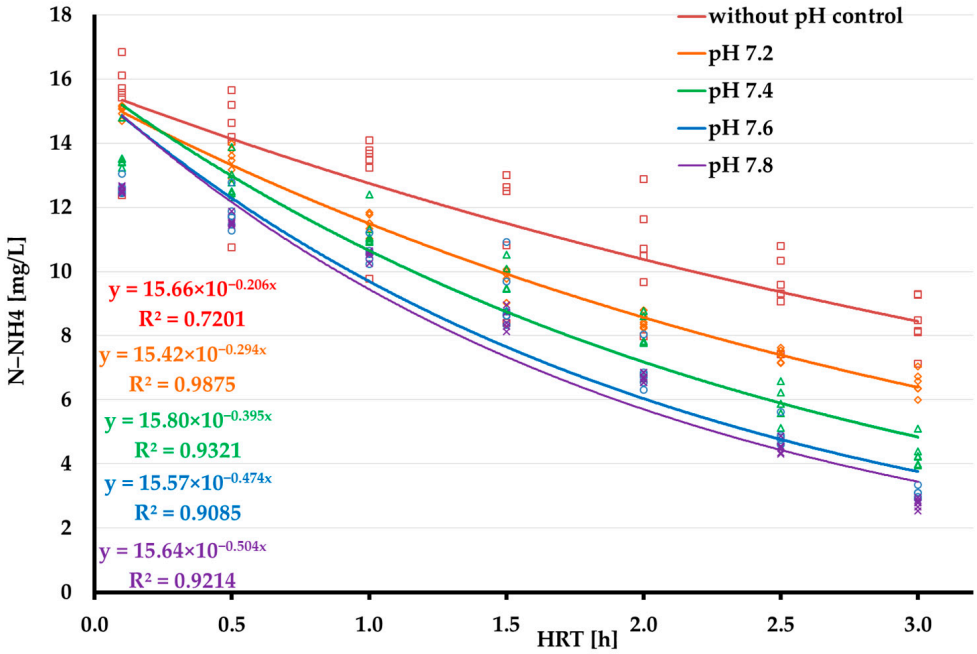


Figure 10. The concentration of N–NH_4 in influent and effluent of model SBR under various pH conditions.

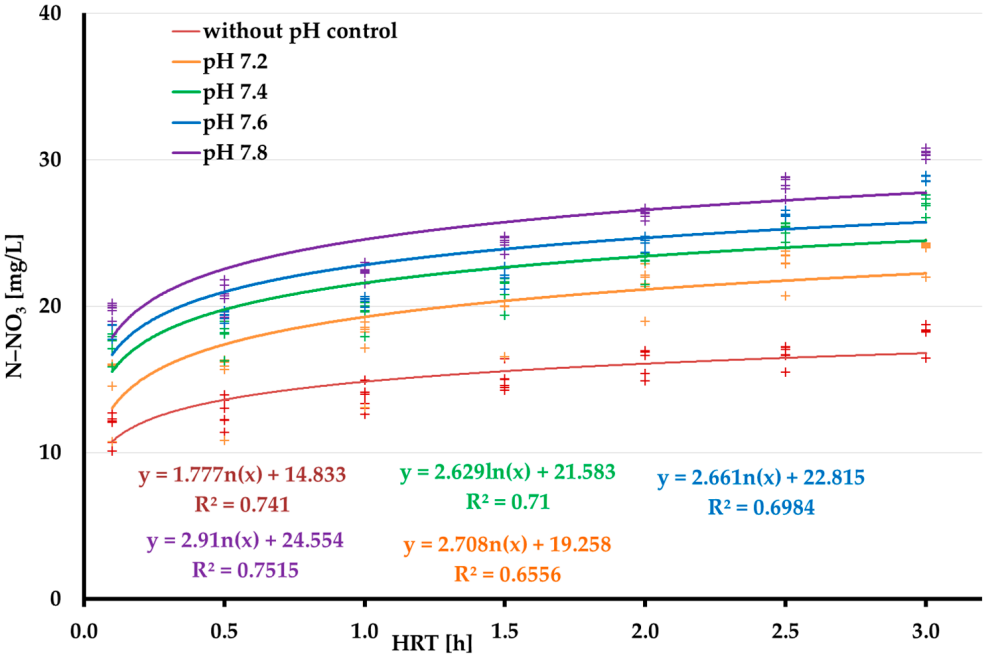


Figure 11. The concentration of N–NO_3 in influent and effluent of model SBR.

After the pH value reached 7.4, the nitrification rate increased. The concentration of N–NH_4 in the effluent was in inverse proportion to the amount of alkali. From a pH value of 7.4 to 7.8, the concentration of pollutants in treated wastewater reached the Vietnamese discharge standard; the concentration of N–NH_4 was lower than 5 mg/L, and the concentration of N–NO_3 was lower than 30 mg/L. The results were obtained under the MLVSS value of 2.1 g/L, which corresponds to previous results from the authors and other researchers [15,37,38].

N–NH_4 and the MLSS dynamics in the reactor allowed for the calculation of the SNR and to compare it with kinetic theory (Figures 12–14).

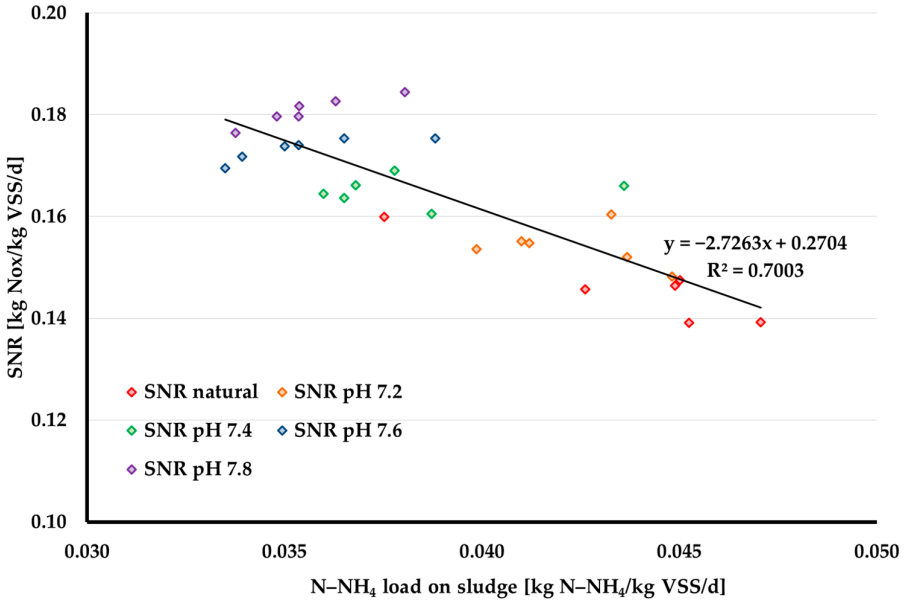


Figure 12. Specific nitrification rate and N–NH_4 load.

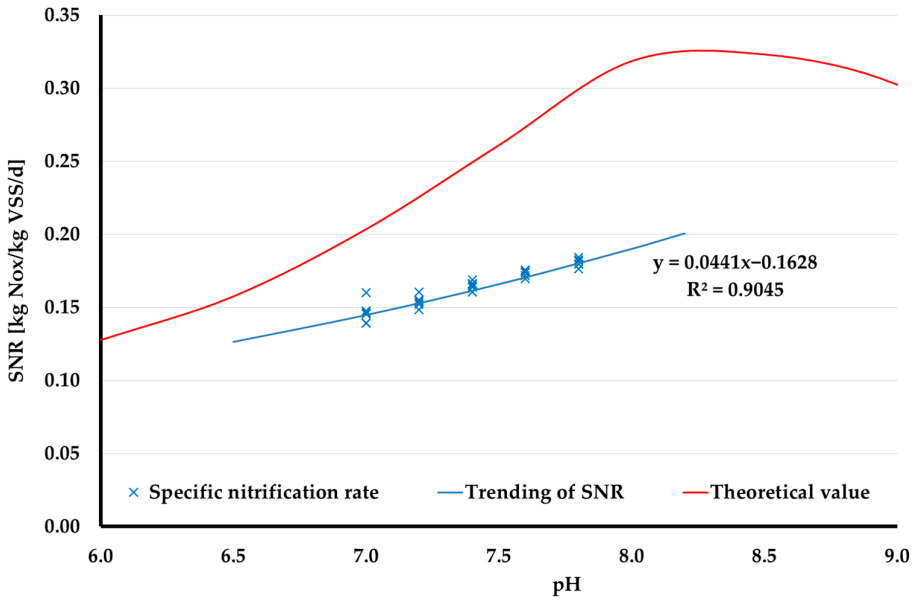


Figure 13. Specific nitrification rate in relation to pH (T = 32 °C).

The SNR is inversely proportional to the loading of ammonia and proportional to the value of pH in the reactor. According to the results of the experiment, with concentrations of MLSS ranging from 2.0 to 2.2 g/L and accounting for 14–16% of the volume of the reactor, the SNR was in the range of 0.16–0.18 kg N_{ox}/kg VSS/d for nitrification in municipal wastewater treatment. At 32 °C, the typical temperature of ASPs in Vietnamese WWTPs, the performance of the biological nitrification was at 50 to 60% when compared with the kinetic theory of pH in reactors in the range of 7.4 to 7.8. The reduction of the SNR by time and its dependence on the pH value in the reactor are presented in Figure 15. The duration of the nitrification in municipal WWTP should be between 1 and 4 h. After 4 h of nitrification and aeration, the amount of ammonia in the influent was almost exhausted, and the rate of reaction tended to zero. Thus, during this stage, empirical data were obtained that differed from the calculated results of similar studies performed earlier. This is primarily due to the ASP temperature, which is considered one of the main limiting factors of the process [30,36].

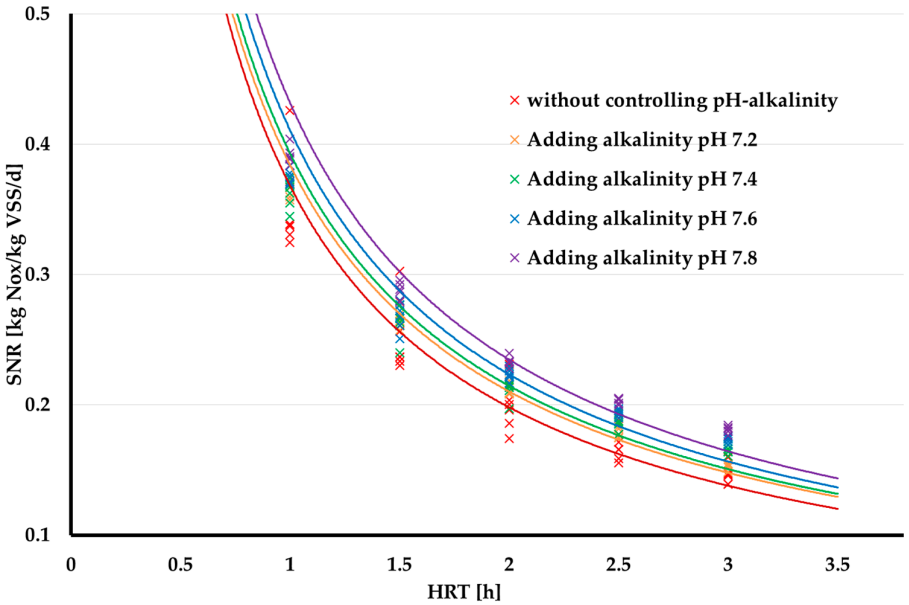


Figure 14. The Specific nitrification rate with adding alkalinity.

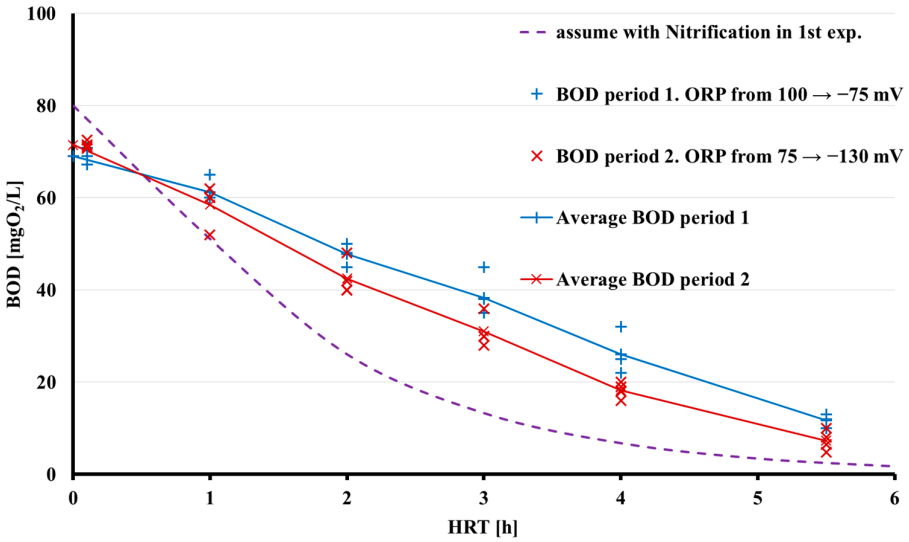


Figure 15. BOD concentration within biochemical Nitrogen Removal.

3.2. The Second Step of Experiment—Biological Denitrification

As far as the carbon source is required for denitrification, heterotrophic microorganisms use organic matter as a source of energy. The filling rate and operation cycle of the SBR have been changed in the second step of the experiment. Changes were made according to recommendations from previous studies [25,28]. The filling rate of the pilot has been increased from 30% (for nitrification) to 50% in order to make use of organic sources in municipal wastewater. The pre-anoxic phase has been applied in the operation cycle for 15 min. The purpose of this phase is to complete the mixing of influent with a high concentration of organic matter and effluent with a high concentration of nitrates. The duration of the denitrification phase is 4 h, and the ORP in the mixed liquor has been controlled. Based on the ORP value in the reactor, the second step of the experiment has been divided into two periods. In the first period, the ORP reduced from 100 to −75 mV, and in the second period, the ORP reduced from 75 to −130 mV. After that, the nitrification process was applied with optimal results from the first step of the experiment. In each period of the experiment, the lab-scale SBR reactor operated for 8 cycles (2 circles of warmup and no sampling), with

the MLVSS remaining at 2.1 g/L and the percentage concentration of activated sludge increasing by 20–22%.

The phase division within the operation circle of the biological nitrogen removal process in pilot was as follows:

- Filling: 15 min
- Pre-Anoxic phase: 15 min
- Denitrification phase: 4.0 h
- Nitrification phase: 1.5 h
- Settling: 30 min
- Discharge: 15 min
- Filling rate: 50% volume of reactor—ensure carbon feed for denitrification reaction (from organic matter in raw wastewater)

From the results of hourly sampling (after pre-anoxic phase) and analysis, the reduction of the pollutants concentration in the SBR is shown in Figures 15–17.

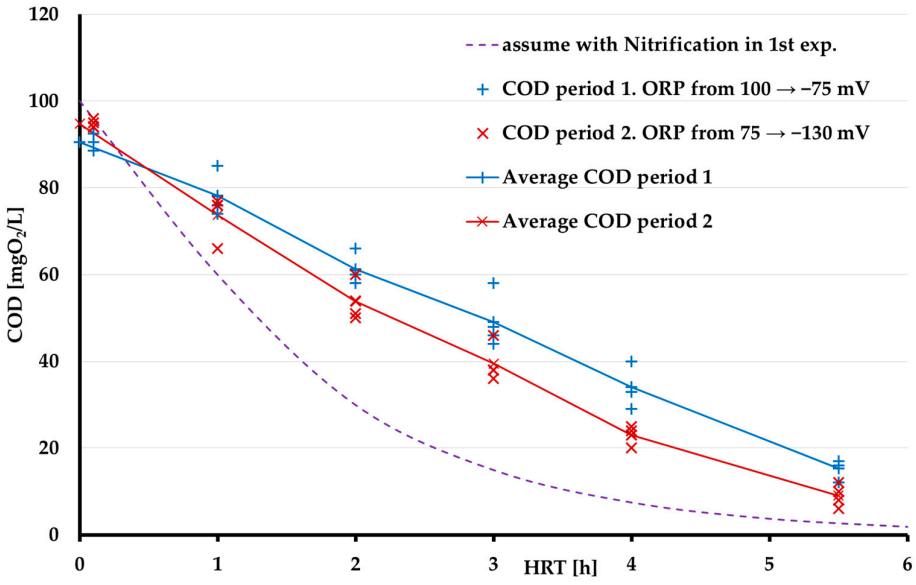


Figure 16. COD concentration within biochemical Nitrogen Removal.

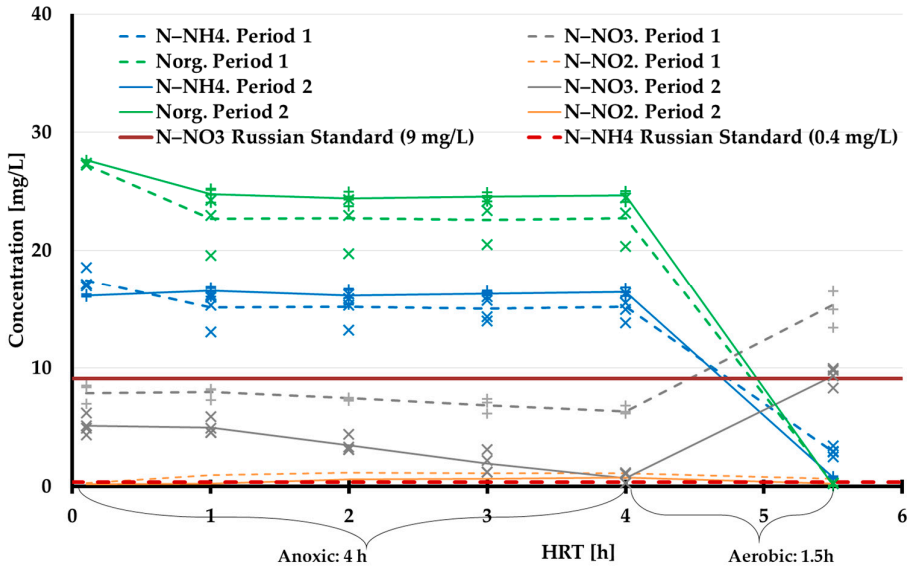


Figure 17. The concentration of Nitrogen in process biochemical Nitrogen Removal.

According to the theory of biological denitrification, in an anoxic environment, heterotrophic microorganisms use organic matter as a source of nutrients and metabolic synthesis as a source of energy. The environmental conditions for biological denitrification reactions are an ORP between 0 and −200 mV and a dissolved oxygen concentration between 0.2 and 2 mg/L. Therefore, the efficiency of the process of removing organic matter expressed in BOD_5 and COD in the second step of the experiment decreases by 5–10% when compared with the first step. The concentration of BOD_5 in the effluent also reaches the discharge standard. On the other hand, the effect of ORP in the reactor is evident in the nitrate concentration after the anoxic phase. Based on the results of the analysis, after the anoxic phase, the average concentration of nitrate in the reactor was 6 and 0.8 mg/L in each period of the experiment, respectively. In the last 1.5 h of biological wastewater treatment, when nitrification occurs in the reactor, the concentration of nitrate in the reactor increases due to the oxidation of ammonia. After settling, only the effluent in the second period of the experiment reached the discharge standard of the Russian Federation. Figures 18 and 19 present the effect of environmental conditions on the performance of reactors.

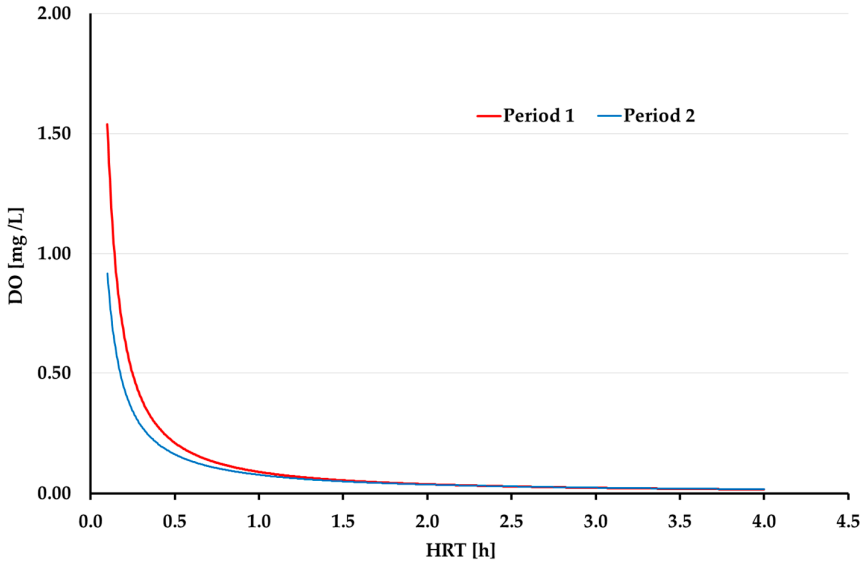


Figure 18. The concentration of DO in SBR reactor within denitrification process.

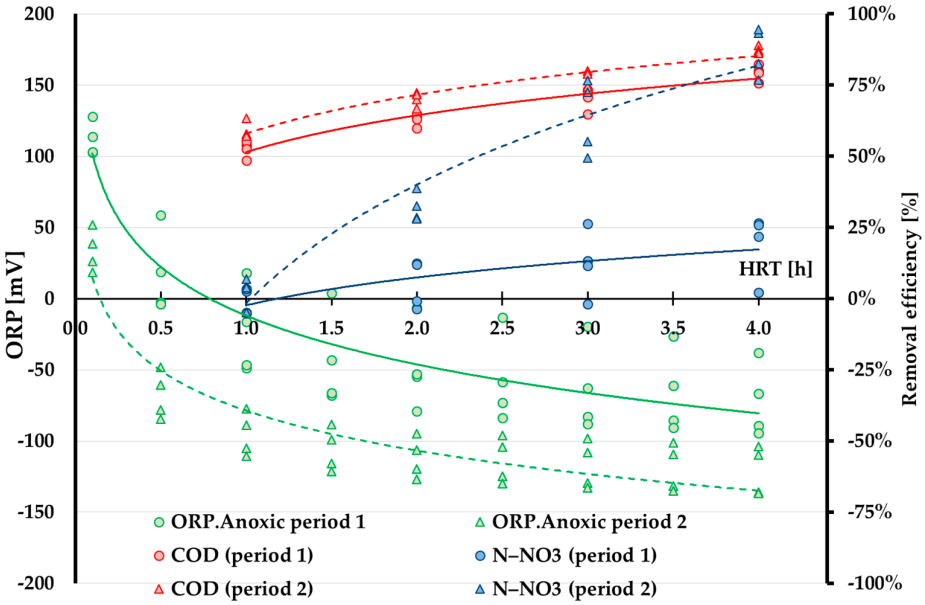


Figure 19. ORP in SBR reactor within denitrification process.

In this experiment, the growth of biomass takes at least 1 h from the beginning of the anoxic step for rapid denitrification. The DO concentration in the reactor reached denitrification's conditions after 15 min, but the ORP of MLVSS required 1.5 to 2.0 h to achieve optimal values. Therefore, due to the same efficiency of organic removal, the denitrification efficiency of each period in the experiment is different, resulting from the decrease of ORP in the anoxic phase of the reactor. In the first period (ORP from 100 to −75 mV), the maximum efficiency of the removal of nitrate in a biological reactor was only 25%. Besides, the performance of process denitrification was in the range of 20–25% in the last 2 h (ORP from −50 mV to −100 mV). However, the efficiency of the removal of nitrate in the second period of the experiment has increased to 70–75% at the end of the denitrification reaction. For 3 h, when the reactor was in anoxic conditions, the quantity of nitrate removed from the reactor reached 50%. Moreover, in this period, the reduction of ORP in the reactor has been supplied for biological denitrification. After 1 h from the pre-anoxic phase, the ORP in the reactor has been decreased gradually to levels of −100 mV and −150 mV at the end of the reaction.

Based on the conditions of growth zones, the relationship between the SDNR and the quantity of organic matter used for biological reactions is shown in Figures 20 and 21.

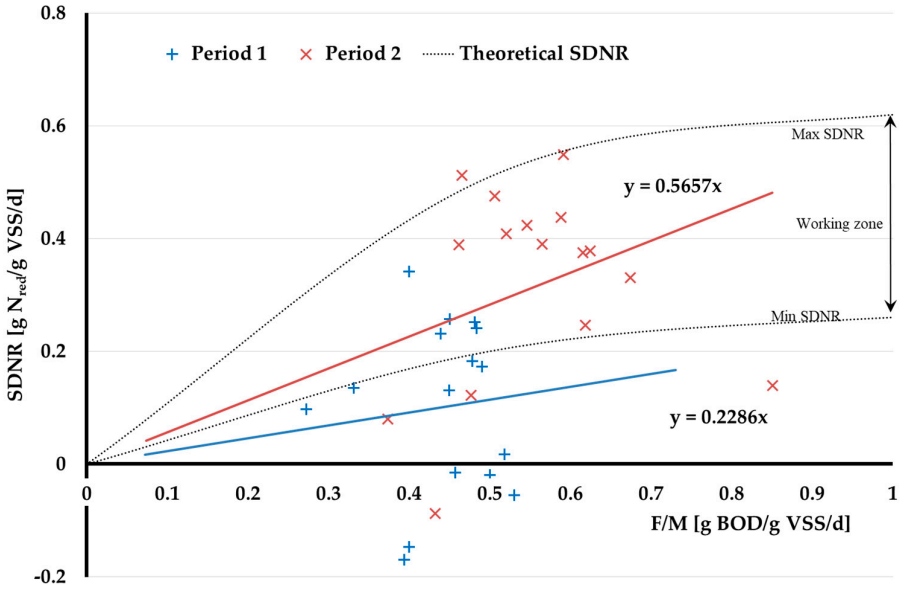


Figure 20. Specific denitrification rate with food to mass ratio in lab-scale SBR.

The SDNR was also affected by anoxic conditions as a result of the varying efficiency of nitrate removal in each period of the experiment. When compared with the theoretical kinetics of food to mass (F/M) ratio (rate of organic matter applied per unit volume of mixed liquor) and SDNR, a quarter of the points in the first period of the experiment were located in the working zone of SDNR. The maximum efficiency of nitrate removal in this period was only 25%, with a SDNR of the reactor lower than 0.25 g N_{red}/g VSS/d; this is consistent with some previous research [39]. On the other hand, with the optimal conditions of DO and ORP, most of the SDNR values in the second period of the experiment were located in the working zone by theory and tend to peak at 0.5 g N_{red}/g VSS/d. After that, the optimal F/M ratio for biological municipal wastewater treatment is in the range of 0.4–0.6 g BOD/g VSS/d. Figure 21 presents the ratio for reducing 1 g of nitrate per unit of BOD in the denitrification reaction. The value of SDNR is proportional to the amount of organic materials used, which were a source of nutrients in the biochemical reaction of nitrogen oxidation [36,40,41]. Therefore, from the first to the second period of the experiment, when the SDNR of the reactor rose from 0.2 to 0.4 g N_{red}/g VSS/d, the ratio N_{red}/BOD_{used} in the biological reactor increased from 0.05 to 0.1. In the second period of the experiment with optimal anoxic conditions, the SDNR of the reactor was in

the range 0.35–0.45 g N_{red}/g VSS/d, and the ratio N_{red}/BOD_{used} was from 0.05 to 0.11. These parameters are the fundamentals for applying biological nitrogen removal to ASP in municipal wastewater treatment without using methanol or another chemical reagent in denitrification [42].

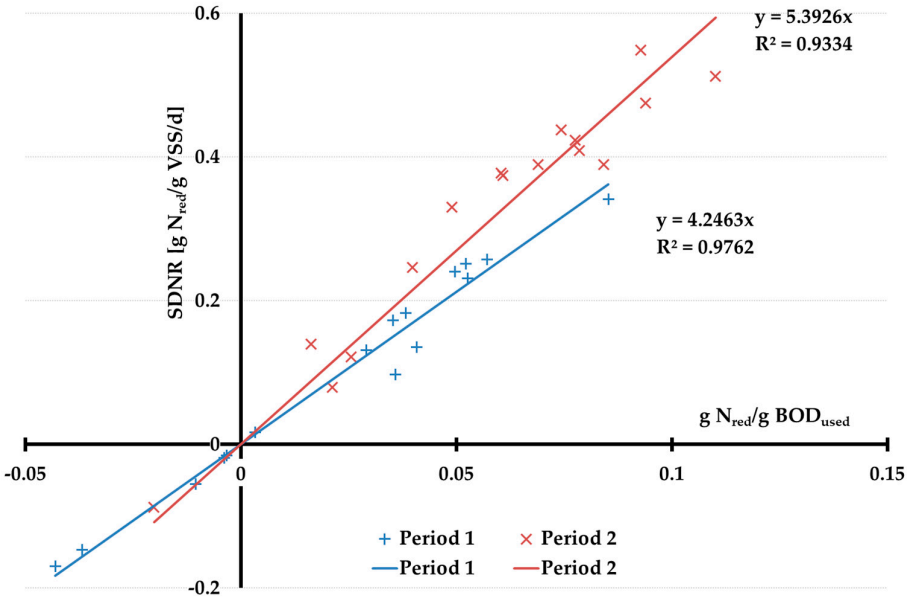


Figure 21. Specific denitrification rate per used organic in lab-scale SBR.

With the addition of the denitrification process in SBR, the mixing process between the mixed liquor and wastewater is very important to ensure the reactor achieves the conditions of denitrification [28]. When the time of the first aerobic phase is 10–15 min and the pH value is 8.3–8.5, the specific rate of denitrification reaches a maximum of 0.43 kg N/kg VSS/day, and the efficiency of the denitrification process is more than 75%. The use of floating feed material has been considered as a tool to improve the efficiency of removing nitrogen compounds in the reactor. According to research [42], the use of feed material in SBR increases the MLSS by 20% under optimal conditions. The rate of substrate utilization and biomass growth in the reactor increases by 10–20%, which leads to a reduction of the biological load on the batch reactor by 15–20% [31].

To consider the efficiency of the SBR technology, several aspects may be focused on in further studies. Aeration improvement is a way to reduce the energy consumption and cost of the WWTP [43]. At the same time, controlling aeration in the reactor and reducing SRT will ensure an increase in the efficiency of nitrogen removal by up to 70%, which also requires further research. Recent studies show that by dosing external carbon feed, aerobic denitrification and phosphatization become possible, for which a short phase of anaerobic wastewater treatment is sufficient to start [44].

Another point of significant interest is the implementation of SBR with zero discharge of sludge, which will have multiple impacts on environmental improvement [45]. There are issues related to organic supplementation, which should significantly accelerate wastewater treatment reactions. This will allow for a reduction in the volume of structures and achieve payback for the decision made. According to modern research, the addition of organic matter, that is, an increase in the C/N ratio, not only increases the rate of heterotrophic processes but also nitrification. At the same time, this opens the possibility for endogenous simultaneous nitrification and denitrification. ESND is suggested to be a promising technology for carbon and nutrient removal under harsh conditions [46]. Besides this, simultaneous nitrification and denitrification in the SBR may be very promising for the conditions in Vietnam, allowing tank volume or area reduction within the facilities [47].

4. Conclusions

1. In the lab-scale SBR for municipal wastewater treatment under low organic matter conditions, adopting multiple anoxic and aerobic processes could enhance simultaneous nitrification and denitrification, and complete nitrification would occur in the final aerobic phase.
2. Treatment of raw wastewater from combined sewerage systems (BOD_5 < 150 mg/L; $N–NH_4$ = 28–30 mg/L) showed an efficiency of organic matter removal of 85–90% and nitrogen removal of 75–80%.
3. For nitrification, the best efficiency was achieved when HRT was 2–4 h and the pH value in SBR in the range from 7.5 to 8.0. The specific nitrification rate under these conditions saw the reactor in the range of 0.18–0.23 kg N_{ox}/kg sludge/d. Overall, this achieving Vietnamese standards for discharge wastewater.
4. For denitrification, optimal HRT was in the range 0.5–2.5 h, which demonstrated a specific denitrification rate in the reactor in the range of 0.35–0.45 kg N_{red}/kg VSS/d.
5. The most efficient reduction of nitrate was 70%, which was achieved if the anoxic phase of the reactor lasts 3–5 h to ensure the ORP reaches optimal conditions, and the F/M ratio of the reactor is from 0.4 to 0.6 g BOD/g VSS/d.
6. Despite the overall positive results, the research should be continued in order to provide stable processes in a wider range of concentration in influent wastewater.

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Abbreviations

ASP	activated sludge process
ASR	activated sludge reactor
BOD	biochemical oxygen demand
COD	chemical oxygen demand
DO	dissolved oxygen
IWA	International Water Association
HRT	hydraulic retention time
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
ORP	redox potential
RAS	recycled activated sludge
SBR	sequenced batch reactor

SDNR	specific denitrification rate
SNR	specific nitrification rate
TN	Total Nitrogen
VSS	volatile suspended solids
WWTP	wastewater treatment plant

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