INFLUENCE OF TEMPERATURE AND RECYCLING RATE ON WASTEWATER TREATMENT PERFORMANCE IN ATTACHED GROWTH SYSTEMS

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Abstract

Attached growth systems such as bio-filters are a commonly used low technology technique for wastewater treatment. However, there is a limited knowledge on the process kinetics and influential parameters of attached growth systems. In this study, the impact of temperature and effluent recycling rate on nitrification and denitrification and chemical oxygen demand (COD) removal processes in attached growth systems were evaluated using experimental batch columns. The equipment consisted of two attached growth reactors in series. The first column was designed to remove carbon and nitrify; while the second column was for denitrification. The average nitrification rate at 20-25°C was 0.86 $g/m^3/d$ of NH_4^+-N with over 6 mg/L DO in the effluent. If the organic loading rate exceeded 2.6 $g/m^3/d$ of COD, nitrification rate was reduced up to 50%. Denitrification occurred by recycling nitrates from the second filter, using the sewage itself as carbon source. The denitrification rate and the hydrolysis of the colloidal COD fraction were found to be strongly dependent on temperature and the recycling rate. Diffusion mass transport plays an important role in attached growth reactor nitrification processes. Consequently, the effect of temperature on the nitrification rate due to bacterial growth rate change is greatly reduced compared with that of suspended growth processes. When oxygen is limited, the decrease in saturation DO concentration as temperature increases will result in a negative temperature impact on the denitrification rate. An appropriate high temperature range (18-28^{0}C) is beneficial for bio-filters, and the hydrolysis of finely dispersed COD particles may be the limiting step in denitrification in attached growth systems when sewage is used as the carbon source.

Keywords

Attached growth systems, bio-filters, denitrification, sewage treatment

1 Introduction

Microbial films attached to a solid surface have commonly been used for small-scale onsite biological wastewater treatment systems in the form of submerged bio-filters, trickling filters and rotating biological contactors. The environmental benefits of achieving nutrient removal in wastewater treatment cannot be disputed. Current evaluations found that there were savings in operating costs of greater than 25% when denitrification is added to a system already achieving nitrification (McClintock *et al.*, 1988). McClintock *et al.*, 1988 and Ip *et al.*, 1987 cite reduced expenditures for energy, and lower sludge handling and disposal costs due to decreased sludge production as factors making nitrogen removal economically attractive in attached growth systems. In the previous studies, researchers have reported on the effect of BOD loading and that of temperature on the behaviour of bacteria and protozoa with reference to the numbers inhabiting the microbial film (for example Hu et al. 1993).

They ascertained that an increase in the viable count of bacteria in the microbial film compensated the decreased activity of individual cells with reduced temperature for BOD removal, while the increased temperature diversified the bacterial population in the microbial film. Observed yields were 35-52% higher for the anoxic reactors than they were for aerobic reactors. The observed yield for the aerobic reactor decreased by 4% with the decline of temperature; whereas the anoxic yield increased by 8% (Lishman *et al*., 2000). Increasing the temperature to a maximum of 42°C of the wastewater will improve living conditions of the biomass and increase the efficiency of the biological treatment process. However there is limited knowledge on the process kinetics and influential parameters of attached growth systems. In this paper, the impact of temperature and effluent recycling rate on nitrification and denitrification and chemical oxygen demand (COD) removal processes in attached growth systems are evaluated using experimental batch columns.

2 Materials and Methods

2.1 Process and operating conditions

In this study, as shown in Fig.1, laboratory scale submerged bio-filters with attached growth systems were constructed. In order to study the influence of temperature and recycling rate on wastewater treatment performance in attached growth systems, a series of experimental tests were conducted. During the six-month period of the simulated experiments, both artificial wastewater and municipal wastewater were treated. The three bio-filters were made from Perspex cylinders with dimensions of 2300 mm high and 150 mm internal diameter. The filters were filled with different media up to 1800 mm depth. Filters were divided into four sections separated by flanges with sampling and monitoring ports incorporated to allow sample control and monitoring for control. Inlets for air and wastewater influent were located at the bottom of the reactors. Wastewater and air flowed upwards through the filter in co-current mode. Details of the operation and maintenance of the experimental setup can be found in previous works. The wastewater was introduced into the anoxic tank with an adequate amount of recirculated treated wastewater, and was left for half a day under anoxic conditions. Effluent from the anoxic tank was fed into the bottom of the bio-filter column. The influent flow into the anoxic tank was controlled using digitally controlled peristaltic pumps. Overall operation of the system including wastewater transfer, distribution of oxygen, anoxic tank mixing, and aeration of the bio-filter was done using a control panel. In order to avoid bio-filter clogging, backwashing at regular intervals was necessary.

In the aerobic parts of the column, aeration was controlled by mass flow with a dissolved oxygen (DO) sensor used for monitoring. It was necessary to maintain DO above 5.0mg/L in the effluent for nitrification, as this would ensure that oxygen is not t a limiting step.

2.2 Media

Bio-filters are biological reactor systems in which contaminants are transformed by micro-organisms in a bio-film growing on the surface of the available medium inside the container. The overall effectiveness of a bio-filter is largely governed by the properties and characteristics of the filter medium, including porosity, compaction, water retention capacity, and ability to host microbial population. The medium should not only provide a good microbial environment, porosity and surface area for microbial attachment; but should also be non-biodegradable and durable. As shown in Fig.2, several types of media were employed here for the project. These were zeolite, porous ceramic filter media and scoria, which is a porous rock of volcanic origin generally used for landscaping. The experiment results obtained for the bio-filter with zeolite are given in this paper.

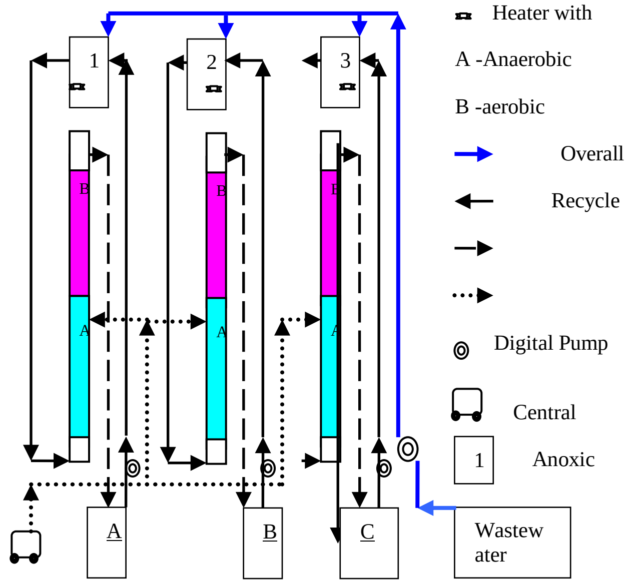

Figure.1: Schematic of the experimental set up

2.3 Sample collection & analysis

The bio-filter was operated at different temperature, recirculation rate and hydraulic retention time (HRT) of 5, 10 and 15 hours, corresponding to hydraulic loadings, organic loading and Total Kjedldahl nitrogen (TKN) loading. Daily observations of effluent quality, including COD, NH3-N and NOx-N concentrations were taken at steady state during the experimental period. The initial hydraulic and organic load to the system was low during the first start-up month, followed by a steady ramp-up. During the six-month period of the simulated experiments, samples were collected and analysed every other day for both grab samples and proportional samples according to Standard Method (APHA, 1995). The biomass was determined as volatile attached solids. The specific activity of the nitrifying bio-film was measured as substrate removal rate per biomass unit. Samples were analysed for TOC, COD, NO_2-N, NO_3-N, TKN, and TP. Ammonium, MLVSS, MLSS, VSS and TSS were measured periodically.

3 Experimental Result and Discussion

3.1 Temperature effects on nitrification and denitrification

Experimental results were used to determine the optimum temperature of nitrification along with the maximum specific growth rates. Past research has found that below around 40^0C, biomass activity increases with increasing temperature, while for temperature over 40^0C, biomass activity rapidly decreases due to degradation. An operating temperature range of 20-25^0C was selected for the study.

Ammonia was initially converted to nitrite as well as to nitrate due to the seeding material and also due to the long aerobic retention time of higher than 1 day and also by allowing the growth of nitrite oxidisers. Nitrite and nitrate were partly denitrified; the nitrite route can be estimated with the assumption that nitrite/nitrate consumption takes place in the same ratio as nitrite/nitrate production (Wang and Wen, 2001).

For denitrification methanol was used as a carbon source. In theory, the minimal stoichiometric demand would amount to 1.9g/g NO_3-N or 1.14g/g NO_2-N denitrified. Considering the biomass yield, the demand was expected to be 3.5 and 2.2g/g N denitrified. After several weeks, when the plant reached steady state the carbon requirement was calculated to be 2.3g/g N denitrified. The decrease of the ratio to 2.3 indicated that there is an efficient use of methanol for denitrification, and also the denitrification has taken place primarily through the nitrite operational conditions in the systems.

3.2 Optimum temperature range for nitrification

Experiments were conducted to determine the optimum temperature of nitrification along with the maximum specific growth rates. The test data indicated that a temperature of up to 40°C, resulted in an increase in biomass activity. For temperature above 40°C, biomass activity rapidly decreases due to degradation. At the temperature of 30-38°C, the ammonium oxidizing biomass give a maximum specific growth rate of 2.2 d^{-1}, resulting in an aerobic time under actual conditions of around 24 hours (Xie *et al*., 2003).

3.3 Temperature effects on COD, TN and TP removal

During the six-month period of the simulated experiments, municipal wastewater was collected from the Loganhome, QLD wastewater treatment plant and used in the experiment as the influent. The experiment was run for different temperatures (12-42°C) and HRT (5, 10, 15 hours), corresponding to hydraulic loadings, organic loading and TKN loading. Daily sampling of effluent quality, including COD and nitrogen concentration were made during the experimental period and were analysed every other day using both grab samples and proportional samples as detailed by APHA (1995). The load on the system was limited during the first month followed by a steady increase. Operational conditions in the system: in the aerobic parts were controlled by mass flow and the DO senor. It was necessary to maintain the DO above 5.0mg/L in the effluent for nitrification. The system performance was investigated according to the differences between influent and effluent water quality. Some average experimental results are presented in Fig.3 and 4. Influent and effluent COD concentrations ranged from 89 to 310 and 10 to 21 mg/L respectively. The effluent COD concentration was strongly dependent on temperature. The temperature range of 20-38°C was considered to be most effective for organics and nutrients removal. When a higher temperature was applied, no significant improvement in system efficiency was observed. If the phosphorus removal is considered important, higher recycle ratios (RR) should be employed. Otherwise, the system could operate with a lower RR.

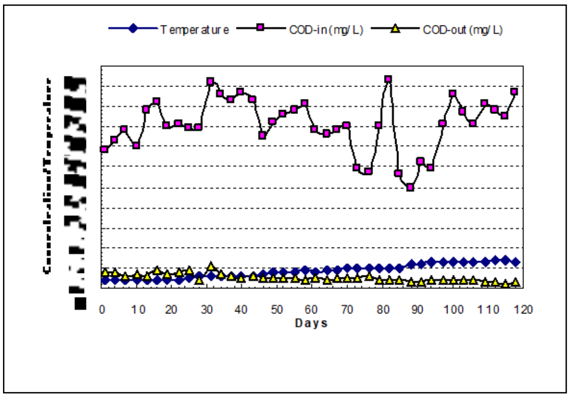

Figure 3: COD concentrations at different temperature over time (RR 1:1.8, HRT=10)

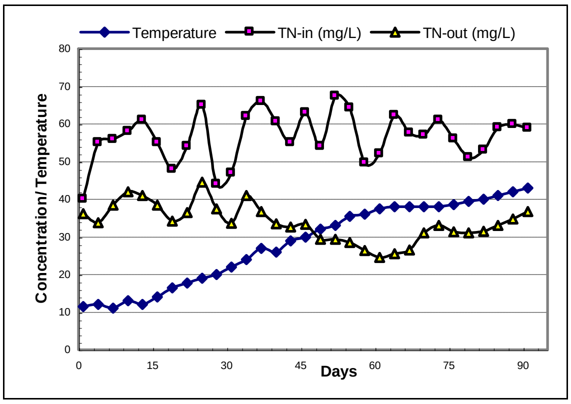

Figure 4: TN concentrations at different temperature over time (RR 1:1.8, HRT=10)

3.4 Recirculation ratio effects on COD removal

The system performance was investigated based on the differences between influent and effluent water quality. Influent and effluent COD concentrations ranged from 89 to 350 and 5 to 21 mg/L, respectively. The effluent COD concentration was strongly dependent on the recirculation ratio (RR). The average effluent concentration decreased significantly from 20 to 5mg/L when the RR increased from 1 to 2.8. However, beyond a RR of 2.8, no further significant improvements occurred. The data suggest that for COD removal, a RR of between 1.8-2.0 is optimal.

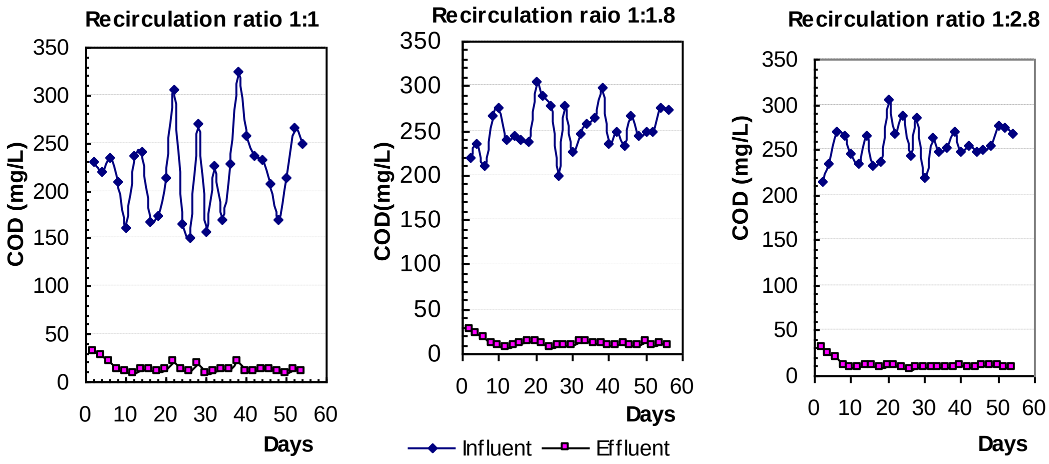

Figure 6: Influent and effluent concentration of COD with different recirculation ratios (HRT=10)

3.5 Recirculation ratio effects on nitrification and denitrification

The removal of the total nitrogen (TN) was accomplished by an aerobic anoxic recirculation mechanism through nitrification and de-nitrification processes. With RR of 1.8 and 2.8, TN concentrations in the effluent were steady and averaged at 11 and 8.5 mg/L respectively. With RR of 1, the average effluent concentration of TN was 14.1 mg/L, which is not considered a suitable effluent water quality for such a system. That is to say, nitrogen can be effectively removed by the proposed anoxic aerobic system as long as RR is more than 1.

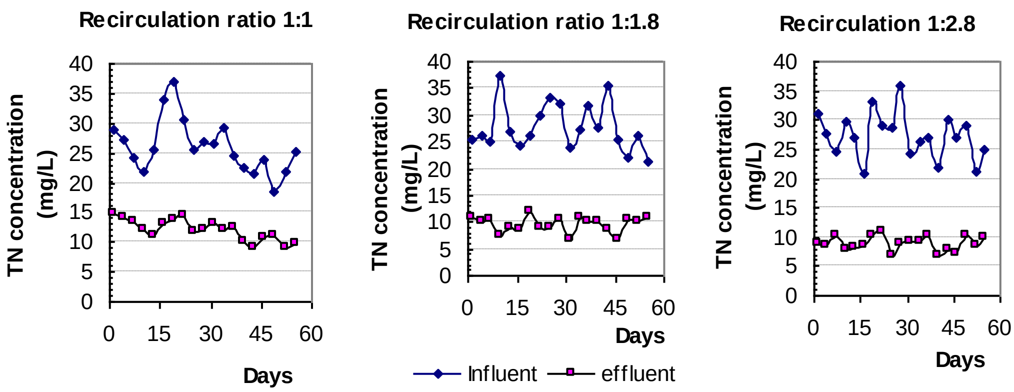

Figure.7: TN concentrations in influent and effluent for different recirculation ratios (HRT=10)

With the constant temperature of 30°C and RR of between 2 and 3, the removal rate of TN was steady and averaged between 41% and 43%. With RR of 1, the removal rate of TN was 26%. With the favourable operating conditions in bio-filter systems, nutrients such as nitrogen and phosphorus were removed effectively by denitrification and nitrification mechanisms. An investigation was also conducted to determine the effluent nitrogen species. As shown in Fig.8, effluent TKN concentrations for the recirculation ratios 1.8 and 2.8 were higher than for recirculation ratio of 1. However, the concentration of NH_3-N was higher at the RR of 1, indicating that the nitrification and denitrification cycle did not treat nutrients effectively. When the RR was increased, the effluent TKN values increased whilst the NO_3-N values decreased. This indicated that the denitrification and nitrification processes occurred more effectively. Considering system efficiency, the range of 1.8-2.2 for RR is considered to be the optimum for removal of nitrogen from wastewater.

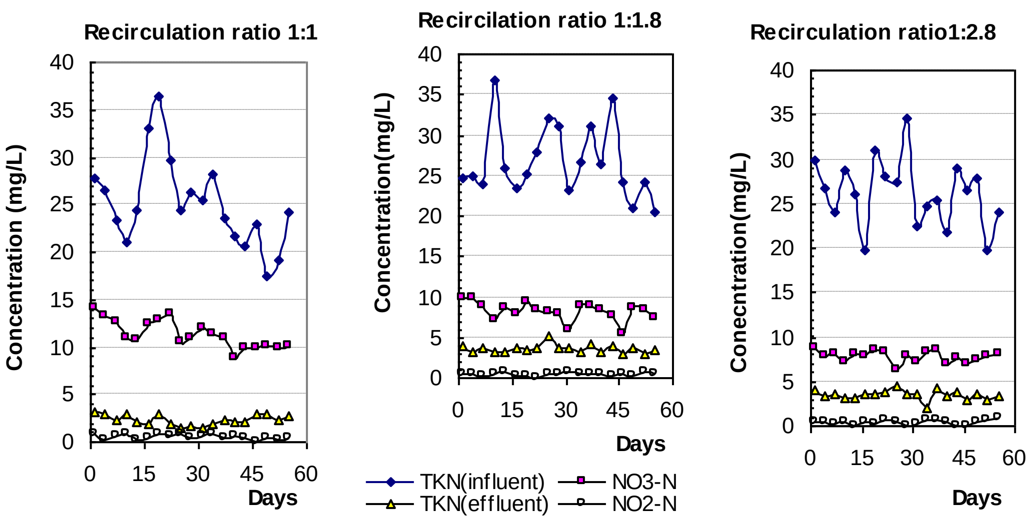

Figure.8: Different nitrogen species in influent and effluent at different recirculation ratios (HRT=10)

Similar results were observed for phosphorus removal. It should be noted that unlike for nitrogen removal, the phosphorus concentration in effluent declined significantly when RR rose from 1.8 to 2.8. As shown in Figure 3, the influence of HRT on nitrification is significant in the aerobic zone. The effect of dilution of nitrifying liquor return caused NH_3-N to drop down in the inlet of the anoxic bio-filter. Although nitrification occurred at lower HRT after a 200 mm height in the aerobic bio-filter, the efficiency of nitrification was so low that NH_3-N concentration kept above 22 mg-N/L and the increase of NO_x-N concentration not significant.

The following experiments were conducted to confirm nutrient removal efficiencies with the proposed anoxic and aerobic recirculating mechanisms. Table 1 summarises the results obtained indicating that ammonium was effectively removed by the system. The total nitrogen removal rate increased slightly from 64.3 to 69.1% as initial ammonium concentration rose from 11.3 to 33.2 mg/L. The total phosphorus removal rate depended more heavily on the initial ammonium concentration. It was found that for higher ammonium influent concentrations of 33.2 mg/L provided the best phosphorus removal. The required amount of phosphorus for microorganisms could be related to the use of ammonium in the system.

Table 1: Nitrogen species and total phosphorus concentrations at points of interest

Indicator items	Initial Ammonium	NH_4^+-N	NO_3^--N	TKN	TN	TP
Influent (mg/L)	11.3	12.4	2.0	28.7	30.1	15.6
Anoxic Effluent (mg/L)		6.7	1.6	10.5	11.4	6.6
Aerobic Effluent (mg/L)		0.2	7.0	3.3	10.4	6.4
Removal Rate (%)		99.6	240.2	87.0	64.3	58.7
Influent (mg/L)	22.0	23.1	2.0	41.3	43.0	21.7
Anoxic Effluent (mg/L)		7.9	4.5	11.2	15.5	4.5
Aerobic Effluent (mg/L)		0.3	12.6	2.7	13.9	3.6
Removal Rate (%)		99.9	-558.1	94.3	67.3	84.1
Influent (mg/L)	33.2	36.1	2.3	53.2	56.5	16.7
Anoxic Effluent (mg/L)		7.8	4.6	12.3	13.7	0.3
Aerobic Effluent (mg/L)		0.1	14.4	3.3	15.1	0.1
Removal Rate (%)		99.9	-64.2	94.5	69.1	99.9

Table 2: Overall wastewater quality and removal rates based on the recirculation ratio

Recirculation Ratio	1	1.8	2.8	1	1.8	2.8	1	1.8	2.8
Indicator	COD			TN			TP		
Influent (mg/L)	223	267.8	247.3	26.1	31.6	24.4	16.3	18.1	18.0
Effluent (mg/L)	10.3	7.7	7.0	13.5	10.9	9.6	8.8	7	2.8
Removal Rate (%)	95.4	97.1	97.0	48.2	65.5	60.6	46.0	59.3	84.4

The attached growth systems removed nutrients satisfactorily. With the recirculation system, nitrogen was effectively removed by denitrification and nitrification. Phosphorus was removed through standard biological demand during COD and TN removal. The range of RR of 1.8-2.0 was most effective for organics and nutrients removal. No significant improvement in system efficiency was observed when a higher RR was applied. If phosphorus removal is important, a higher RR should be employed; if not, the system could operate with a lower RR.

An investigation was also conducted to determine the effluent nitrogen species. Effluent TKN concentrations for a RR of 1 were lower than for RR of 2 and 3. However, the concentration of NH_3-N was higher at the RR of 1, indicating that the nitrification and denitrification cycle did not treat nutrients effectively. When the RR was increased, the effluent TKN value increased, whilst the NO_3-N values decreased. This indicates that the denitrification and nitrification processes occurred more effectively.

More than 90% COD can be eliminated by the bio-filter system. However, the efficiency of nitrogen removal is closely related to HRT and temperature in the bio-filter system. The increase of hydraulic and organic loading relates to the decrease in retention time and a decrease in treated water quantity. In the system, both physical adsorption and biological reactions are the main mechanisms in pollutant removal. Since the bio-film is fixed in the media of the bio-filters, the influence of diffusion on biological reactions are significant. With a longer HRT, it could result in sufficient retention time for promoting diffusion of pollutants between the bulk solution and the bio-film.

From the DO concentration and oxidation/reduction potential, the reactive condition of the electronic acceptor could be confirmed in the system (Ouyang et al., 2000). At bench pilot tests, biological reactions in COD oxidisation was evident in the first 200-250 mm height of the aerobic bio-filter, with more DO being consumed in the 250-650 mm height of the aerobic bio-filter. Biological reactions become slower with the increase in bio-filter height, so DO increased with bio-filter height from 3 mg/L to 5 mg/L.DO was consumed more at the low HRT. This is due to more organic loading for low HRT (Yu and Xie, 2002). The average nitrification rate at 20-25^{o}C was 0.86 g/m3/d of NH4+-N with over 6 mg/L DO in the effluent. If the organic loading rate exceeded 2.6 g/m2/d of COD, nitrification rate would reduce up to 50%. The denitrification occurred by recycling nitrates from the second filter and by using sewage itself as carbon source.

According to Rittmann and McCarty (1980), TKN transport from wastewater into a fixed bio-film is a diffusion-controlled process. There is a minimum substrate concentration that must be maintained in the bulk water in order to create a concentration gradient across the bio-film. A minimum TKN concentration was needed to support a steady-state nitrification bio-film. At a temperature of 27^{0}C, the minimum TKN concentration was 0.07 mg/L (Zhu and Chen, 1999). An adequate concentration of substrate is essential to support a stable nitrifier population. Recirculation of effluent from the aerobic zone can not only improve the efficiency of mass transfer and increase the DO concentration, but also decrease the fluctuation of the organic load, so augmenting the RR will more efficiently remove nutrients.

4 Conclusions

With favourable operating conditions, nutrients can be transformed and removed effectively by denitrification and nitrification in attached growth systems. The denitrification rate and the hydrolysis of the colloidal COD fraction were found to be strongly dependent on temperature and recycling rate. Diffusion mass transport plays an important role in attached growth reactor nitrification processes. Consequently, the effect of temperature on the nitrification rate due to bacterial growth rate change is greatly reduced compared with that of suspended growth processes. It was necessary to maintain DO above 5.0 mg/L in the effluent for nitrification. Considering a range of factors in the system, an appropriate high temperature range (18-28^{0}C) is beneficial for bio-filters. The hydrolysis of finely dispersed COD particles can be the limiting step in denitrification in attached growth systems when sewage is the carbon source.

RR between 1.8-2.0 is optimal for COD removal. Removal of TN was by an aerobic anoxic recirculation mechanism using nitrification and de-nitrification processes. With the constant temperature of 30^{0}C and RR of 1.8 - 2.8, TN removal rate was steady and averaged 41-43%.

The average nitrification rate at 20-25^{o}C was 0.86 g/m^3/d of $NH4^+$-N with over 6 mg/L DO in the effluent. If the organic loading rate exceeded 2.6 g/m^2/d of COD, nitrification rate would reduce by up to 50%. The denitrification occurred by recycling nitrates from the second filter and using sewage itself as carbon source.

The range of temperature and RR of 18-28^{0}C and 1.8-2.0 respectively, is considered to be most effective for organics and nutrients removal in attached growth systems. If the phosphorus removal is considered important, the higher RR should be employed. Otherwise, the system could operate with a lower RR. In any particular case, the RR will depend on the source wastewater and the objectives of the facility. It is worthwhile to focus future research on how to enhance energy and oxygen utilisation.

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