Effluent Recirculation in Slag Media Trickling Filter for Enhanced Organic and Nitrogen Removal

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Summary: Blast furnace slag, a waste material of the steel industry, was investigated on laboratory scale as a filter media. Organic removal efficiency was influenced by the organic loading rate. Biological oxygen demand (BOD) removal efficiency was found to decrease gradually from 93.5% to 81.4% by increasing the organic loading rate from 0.27 to 0.44 kg BOD $m^{-3} \cdot d^{-1}$. Ammonia-nitrogen (NH_4-N) removal efficiency was also decreased from 86.3% to 72.1% in the same range of organic loading rates. Employing effluent recirculation under various operating conditions, improvements in the existing removal efficiencies of BOD and NH_4-N in comparison to the non-recirculation regimes were found, improvement being in the ranges; BOD (5.3-9.9%) and NH_4-N (3.4-16.5%). The results indicate a ratio of 3.72 g $BOD_{utilized}$ $g^{-1}N_{removed}$ that is 2.3 times less than the previously reported ratio of 8.6 g $BOD_{utilized}$ g^{-1} $N_{removed}$ in BNR processes. The slag media trickling filter has the potential to be used as an appropriate process for the treatment of small sewage in rural areas. To summarize, utilization of slag as a filter media in a trickling filter process provides a beneficial usage of this material.

Introduction

Burgeoning nitrogen and organic pollution have badly deteriorated the water quality in different aquifers and contributed to increasing eutrophication and depletion of dissolved oxygen, which have in turn resulted in a significant decrease in fish population in the receiving water bodies. Excessive application of fertilizers and intensive animal rearing are the major sources of nitrogen pollution [1]. It has been estimated [2] that one-kilogram of nitrogen, on complete assimilation, will produce 16 kg of algal biomass, which is equivalent to 20 kg of chemical oxygen demand (COD). So considered, a discharge of 30 mgl^{-1} of nitrogen, a usual nitrogen (N) concentration in domestic wastewater in Korea [3], would result in the production of COD equivalent to 600 mgl^{-1}, which is almost three times that of normal COD of the domestic wastewaters in Korea. The usual COD range is 180-200 mgl^{-1}, classified as low strength [3].

Blast furnace slag is a waste material produced in the steel industry. In Korea, during the period of 1987-1995, the annual average production of steel at Pohang Steel Company (POSCO), one of the world-renowned steel industries, was over 10 million tons with a waste generation including blast furnace slag of about 6.6 million tons. Although a portion of the slag waste is used as road material, cement ingredient, building material, etc., the remaining part remains unutilized and is disposed of as landfill material.

The trickling filter process is widely accepted and used for aerobic biological treatment of wastewater. It is used for the removal of both organic matter and nitrification [4]. A nitrifying trickling filter, which is considered simple to operate, has lowered operational and maintenance cost than many other tertiary processes [5]. Several researchers [4,6-7] have used different types of media. Different mineral media were used for enhanced nitrogen removal in trickling filters. Gray and Learner [6] used plastic, mixed media, and blast furnace slag. They reported that blast furnace slag is the third most commonly used filter media (23 %) after clinker (24 %) and granite (26 %) in Britain. Hawkes and Jenkins [8] reported that blast furnace slag has a rough texture with a high voidage. The 50 mm grading was regarded as the most appropriate size to get a high quality effluent, the material that meets the British Standards specification [8]. Slag media has been found [6] to be more effective in the removal of ammonia at a lower loading rate than mixed media or

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a plastic filter, yet a mixed media was recommended owing to its markedly greater efficiency compared to slag filters. However, slag media has the capability to accumulate significantly more biofilm than either the mixed or plastic filters at the lowest loading, a maximum film weight being far more than that recorded in other filters [6].

Due to poor sewerage system in South Korea, the government has initiated its efforts in 2002 for the improvement of the existing system. On the other hand, since 1995 small sewage treatment projects in Korea have gained momentum to develop sustainable treatment technologies to be used in small communities so that better living conditions could be provided and to prevent water bodies from further deterioration. The Korean government is supporting the initial cost for the construction of treatment facilities, but high expenditures for operating and maintenance are borne by the users. For these reasons, a sustainable and economically feasible treatment process with good nutrient removal efficiency is needed for rural areas. In order to meet the above requirements, many kinds of small-scale sewage treatment facilities like extended aeration, rotating biological contactors, etc. has been considered for biological nitrogen removal. Among the tertiary attached growth processes, the nitrifying trickling filter is appealing because of its simplicity and lower operational, capital, and maintenance costs when compared to many of the other tertiary processes [5]. This paper examines and compares the present system of the slag media trickling filters with those reported previously for enhanced organic and nitrogen removal with special emphasis on the effluent recirculation and non-recirculation regimes.

Results and Discussion

a. Organic removal

It is generally accepted that BOD removal is more dependent on the organic loading rate (OLR) than the hydraulic loading rate (HLR). The organic loading rate (0.27-0.44 kg BOD $m^{-3}\cdot d^{-1}$) was employed (Table 1) in the present investigation in order to facilitate enhanced removal of organics and for improved nitrification. Operational experience for a small wastewater treatment plant in Holland, as mentioned by Fastenau *et al.*, [9], and in France, by Racault and Vachon [10], showed a good performance on the organic loading rate at 0.4 and 0.2 kg BOD $m^{-3}\cdot d^{-1}$ respectively. The range of the organic loading rate, as studied in the present work, coincides with that of the reported data [10]. Results in Figure 1 show variations in BOD concentration and its removal with time at different modes. The data (Figure 1) clearly demonstrate that removal of soluble BOD (SBOD) and total BOD (TBOD) was high in modes 2, 4, 5, 7, and 9 compared to the remaining modes 1, 3, 6, and 8. The main reason for this effect is the effluent recirculation. All these modes had 100% effluent recirculation except in mode 5 where it was 200%. The data (Figure 1) do not show any marked differences in the TBOD and SBOD removal efficiencies whether the system was operated at a recirculation ratio of 100 or 200%. The effluent quality at modes 1, 3, 6, and 8 was slightly poor compared to the rest of the modes, suggesting that effluent recirculation enhanced the quality of effluent. The data in Figure 2 show BOD removal efficiencies and the organic loading rate. The results of the present study have also been compared with the published results (Figure 2). This figure clearly

Table 1. BOD/T-N ratio at each mode of the slag media trickling filter

Mode	Effluent recirculation ratio (%)	BOD/T-N ratio* ($mg\ BOD_{utilized}\ mg^{-1}\ T\text{-}N_{removed}$)
1	0	3.218
2	100	3.240
3	0	3.271
4	100	3.270
5	200	3.521
6	0	3.138
7	100	3.308
8	0	3.364
9	100	3.226

* Mean values of about 10 readings

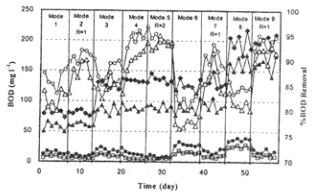

Fig. 1: Variations between BOD concentrations and percent BOD removal with time during recirculation and non-recirculation regimes
○ Soluble BOD removed △ Total BOD removed
◆ Total BOD (influent) ▲Soluble BOD (influent)
● Total BOD (effluent) □Soluble BOD (effluent)

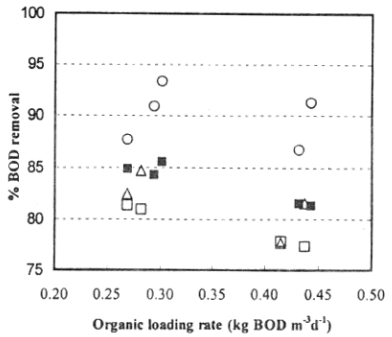

Fig. 2. Effect of the BOD loading rate on the removal efficiency of BOD, comparison of the slag media trickling filter results with the published data in their recirculation and non-recirculation modes
△ This study (without recirculation)
□ NRC [11] (without recirculation)
○ This study (with recirculation)
■ NRC [11] (with recirculation)

demonstrates three main differences between the present and reported results [11]. First, the present study shows enhanced BOD removal compared to the reported results [11], both in their recirculation and non-recirculation regimes. Second, recirculation of the effluent to the trickling filter markedly enhanced the BOD removal efficiency. Third, a gradual decrease in the BOD removal efficiency was apparent when the organic loading rate was increased from 0.27 to 0.44 kg BOD $m^{-3} \cdot d^{-1}$, both in the present and the reported results.

The decrease in BOD removal with the increase in organic loading is a normal trend, which has been discussed by several workers [4, 11]. The reasons for this effect are sloughing of the biofilm and lower contact time of the organics in the influent with microorganism when the organic loading rate was increased. Furthermore, it has been reported [4] that in trickling filters that accomplish either carbon oxidation or combined carbon oxidation and nitrification, it is likely that oxygen is the limiting substance, especially at higher organic loading rates. When both biodegradable organic matter and ammonia-nitrogen are present, heterotrophs and autotrophs compete for space in the aerobic portion of the biofilm, with autotrophs being excluded until the concentration of the biodegradable organic matter drops below 20 mg l^{-1} as COD [4]. Therefore, if the rate of oxygen transfer into the biofilm is limited especially in the upper portion of the trickling filter, then the oxidation rate of biodegradable organic matter will be limited by the rate of oxygen transfer [3]. The slag media trickling filter however, showed better removal efficiency (Figure 3) than the reported results [11] due to improved wetting and flushing of filter media. Statistically, the correlation that was established (data not presented here) while using the regression curve in the organic loading rate range of 0.27-0.44 kg BOD $m^{-3} \cdot d^{-1}$ confirms that the existing slag media system with effluent recirculation has better organic removal efficiency than that of other reported media [11] or those in the non-recirculation modes:

- BOD removal rate (without recirculation) = 0.805 × BOD loading rate
- BOD removal rate (with recirculation) = 0.896 × BOD loading rate

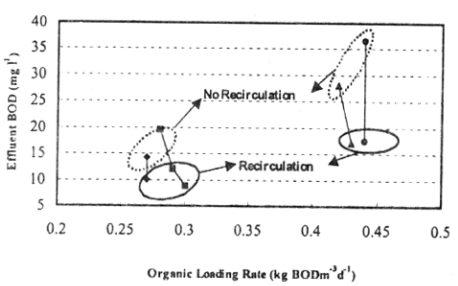

Fig. 3. Effect of the organic loading rate on the effluent BOD, in the recirculation and non-recirculation modes of slag media trickling filter
◆ Mode 1, 2 ■ Mode 3, 4, 5
▲ Mode 6, 7 ● Mode 8, 9

The marked increase in the BOD removal efficiency when the effluent of the trickling filter was recirculated is attributed to the dilution [4] of organics in the influent during a higher organic loading rate. At a relatively higher organic strength (COD > 250 mg l^{-1}), O_2 limitation is expected; therefore, recirculation is helpful in diluting the influent. Furthermore, recirculation also reduces odour emissions [4]. The differences of the present results with- and without-recirculation have been compared to those of previously reported results [11]. Under the same experimental conditions, BOD removal efficiency with 100% recirculation was higher than those devoid of recirculation. The net

increase was found to be in the range of 5.3-9.9%. However, a further increase in the ratio of recirculation (200%) did not impart any marked increase in the BOD removal. The data in Figure 3 show the effect of organic loading rate on the effluent quality at different modes in the recirculation and non-recirculation regimes. The figure clearly demonstrates that slag media with recirculation produce good quality effluent, especially in modes, 3, 4, and 5 where effluents of 8-13 mg BOD l^{-1} at lower loading rate were produced (Figure 3) compared to 17-18 mg BOD l^{-1} at a higher loading rates in modes 8 and 9. On the contrary, there are some reported cases that do not conform to the normal behaviour of increase in the removal efficiencies with recirculation. For example, Evangelho *et al.*, [12] have reported that recirculation decreased the efficiency of metal removal and correlated this effect mainly to a drop in pH. Similarly, Vayenas and Lyberatos [13] found that recirculation had an adverse effect at low hydraulic loading rates.

b. Nitrogen removal

Results related to variations in the concentration and removal of different forms of nitrogen with time at different modes of the slag media trickling filter are presented in Figure 4. More or less similar trends were found in the variations and removal of nitrogen that can be regarded as identical to the BOD removal (Figure 1) trends discussed in the preceding section. NH_4-N removal (Figure 4) in

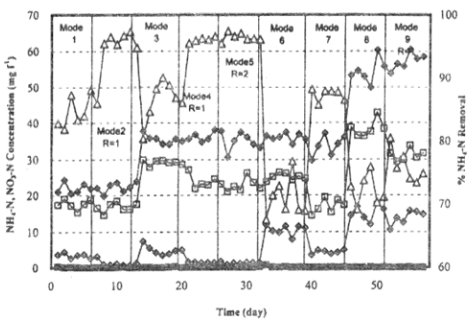

Fig. 4. Variations in the concentration of different forms of nitrogen and percent removal of ammonia with time during circulation and non-recirculation regimes

△ NH_4-N (removed) ◆ NH_4-N (influent)
□ NO_3-N (effluent) ◇ NH_4-N (effluent)
■ NO_3 –N (influent)

modes 2, 4, 5, 7, and 9 was high due to effluent recirculation compared to the modes 1, 3, 6, and 8 where the trickling filter operated without any effluent recirculation. The data in Figure 4 reveal that effluent quality with regards to NO_3-N was quite high, but effluent quality due to NH_4-N was poor. Effluent recirculation compared to non-recirculated regimes contributed to improving the effluent quality. Effluent NH_4-N concentrations in modes 2, 4, and 5 were significantly lower (0-3 mg l^{-1}), but effluent quality deteriorated in mode 9 where NH_4-N concentrations varied between 10 and 16 mg l^{-1}. This increase can be attributed to the abrupt increase in the influent NH_4-N concentration where it increased from average 35 mg l^{-1} (in modes 3-7) to as high as 60 mg l^{-1}, the concentration being varying in the range of 50-60 mg l^{-1} in modes 8 and 9. Data in Figure 4 suggest that with 100% recirculation, the system operated at influent NH_4-N in the concentration range of 20-38 mg l^{-1} produced acceptable effluent quality. On the other hand, with recirculation, influent NH_4-N exceeding this range, it was difficult to achieve effluent quality below 15 mg $l^{-1}$of average concentration of NH_4-N.

The data in Figure 5 show NH_4-N removal efficiency at different organic loading rates. The results indicate that the ammonia removal efficiency decreased with the increase in the organic loading rate. This behaviour is not at variance with the previously published results [4, 6, 14]. For example, Gray and Learner [6] have reported that ammonia removal efficiency decreased with the increase in the organic loading rate. Stenquist *et al.* [15] reported that organic loadings limit nitrification, as nitrifying bacteria at higher organic loadings are lost as a result of greater sloughing. The data in Figure 5 suggest that varying BOD loading rates in the range of 0.27-0.44 kg $m^{-3} \cdot d^{-1}$ without recirculation, NH_4-N removal efficiency gradually decreased from 86.3 to 72.1%, producing effluent concentrations of 4.8 to 15.2 mg l^{-1}. The data in the present study (Figure 5) have also been compared with the reported results of Parker and Richards [14] in their recirculation and non-recirculation regimes. The results of Parker and Richards [14] show that the degree of nitrification (Figure 5) decreased almost linearly with the increase in organic loading rate (with recirculation), reducing NH_4-N removal from 90 % at organic loading rates of less than 0.1 kg BOD m^{-3} d^{-1} to about 50% at an organic loading rate of 0.3 kg BOD $m^{-3} \cdot d^{-1}$. On the other hand, slag media trickling filter achieved over

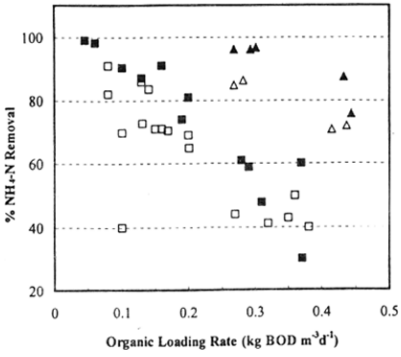

Fig. 5 Nitrification efficiency and BOD volumetric loading rate, comparison of the slag media with published data in their recirculation and non- recirculation modes
△ This study (without recirculation)
□ Parker *et al* [5] (without recirculation)
▲ This study (with recirculation)
■ Parker *et al* [5] (with recirculation)

82% higher degree of nitrification at the same loading rate (0.3 kg BOD $m^{-3} \cdot d^{-1}$) even in the absence of recirculation. With recirculation throughout, 3.4-16.5% increase was recorded in the ammonia removal under the same operating condition. Likewise organic removal, for ammonia removal, the correlation from regression curve (data not presented here) in the range of 0.54-0.94 g NH_4-N $m^{-3} \cdot d^{-1}$ was found to be:

- NH_4-N removal rate (without recirculation) = 0.755 × NH_4-N loading rate
- NH_4-N removal rate (with 100% recirculation) = 0.847 × NH_4-N loading rate

Figure 6 shows the results of denitrification where its efficiency was increased from 13 to 42 % by varying the effluent recirculation ratio from 0 to 200%. The data (Figure 6) suggest that the denitrification rate and T-N removal reached a peak in mode 7, where effluent recirculation was 100%. Parker *et al.*, [5] have reported opposite results, where a decline was found in the nitrification performance of a tertiary nitrifying trickling filter. This was attributed to the presence of predators, which were found in the Littleton/Englewood wastewater treatment plant in the USA. This was successfully corrected by biofilm control measures

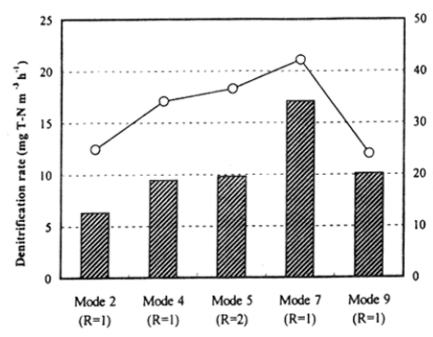

Fig. 6: Rate of denitrification and loss of total nitrogen at different modes of the slag media trickling filter
▨ Denitrification rate ○ Total nitrogen removal

[5]. Furthermore, high hydraulic loading rates have been found to improve nitrification process performance [5]. Because of effluent recirculation, the normal absence of nitrate at the top of the filter can be attributed to the denitrification of recycled nitrate as well as to the absence of nitrate generation at the upper part of the media in the trickling filter. Feeding of high NO_3-N concentrations and proper organics for denitrification caused T-N removal at higher loadings. Effluent recirculation is therefore more effective than non-recirculation for the removal of organic and nitrogen. Furthermore, statistical analysis suggests that for highest removal of T-N, the organic and nitrogen loading rates should be 0.37 kg BOD $m^{-3} \cdot d^{-1}$ and 100 g NH_4-N $m^{-3} \cdot d^{-1}$ respectively. A relationship between these two parameters is shown in Figure 7 that suggests a direct relationship between the two with 99% confidence limit and a slope of 3.72 g BOD g^{-1} NH_4-N removed. In other

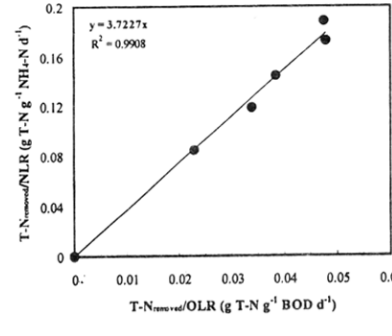

Fig. 7. Relationship between nitrogen and organic loading rates

words, at least 3.72 g of BOD is required to remove 1 g of nitrogen; this indicates substantial nitrogen removal at the expense of very low BOD. This ratio is of significance, as it has been reported previously [16] that 8.60 g of BOD is required to remove 1 g of nitrogen in Biological nutrient removal (BNR)qq system. On this basis, the present system is around 2.3 times more effective in the removal of nitrogen compared to that in the BNR systems. This argument can further be substantiated by the data presented in Table 1 where the mean values of $BOD_{consumed}$/T-$N_{removed}$ both at the effluent recircula-tion and non-recirculation modes are given. The data (Table 1) do not show any appreciable difference in the amounts of BOD consumed for the removal of unit nitrogen regardless of the effluent recirculation ratio. The average ratio with 100% recirculation, as calculated from Table 1, is 3.26 mg $BOD_{utilized}$ mg^{-1} T-$N_{removed}$ whereas the average ratio of the system devoid of recirculation is 3.25 mg $BOD_{utilized}$ mg^{-1} T-$N_{removed}$. The overall ratio of the existing system of slag media trickling filter (Table 1) is on the average 3.284 mg $BOD_{utilized}$ mg^{-1} T-$N_{removed}$. Considering the average values of Table 1, it can be argued that the present slag media trickling filter is around 2.6 times more effective than BNR [16] systems due to low biodegradable COD requirements, the two values (2.3 and 2.6) supporting the claim. Low BOD requirement is of great significance as sewage in Korea is of low strength and this is one of the reasons that hinder application of BNR processes [3].

Higher performance of the existing trickling filter is attributable to the filter media that is capable of developing an efficient biofilm for the enhanced nitrification rates. A higher nitrification rate can also be due to the optimum range of hydraulic loading rate (3.54-5.31 m^3 m^{-2}·d^{-1}) as a higher hydraulic loading rate has been implicated in improved nitrification performance [5]. Furthermore, pH of the system was maintained in a range that was optimum for nitrification as reported by Koren *et al.*, [17]. Similarly, it is more likely that organic loading rates in the range of 0.27-0.44 kg BOD m^{-3}·d^{-1} might be optimum as well and well-matched to the system for improved ammonia removal efficiency, yet this needs to be confirmed.

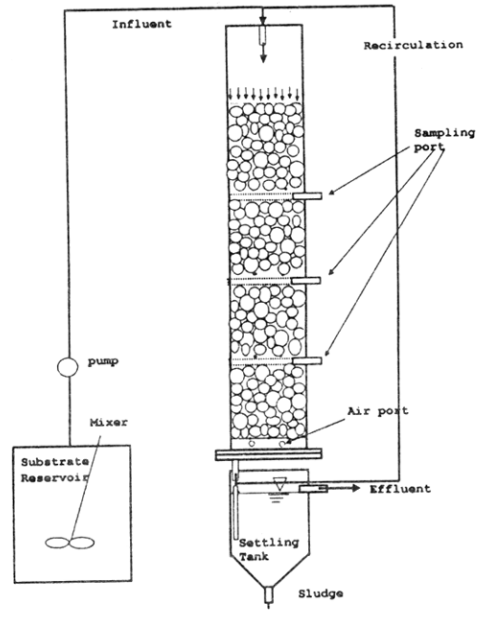

Fig. 8. Schematic diagram of the laboratory scale slag media trickling filter unit

Experimental

The schematic diagram of the laboratory scale trickling filter, made of transparent acrylic resin, is shown in Figure 8, where slag was filled as biofilm media. Slag with a diameter of 2.5-3.5 cm was used, depth was maintained at 160 cm, and specific surface area and void ratio were found to be 135 m^2m^{-3} and 47 % respectively. For the removal of suspended solids and recirculation of effluent, a rectangular type of clarifier was placed below the trickling filter.

Table 2. Experimental conditions of the trickling filters

Item	Case 1 (modes)		Case 2 (modes)					Case 3 (modes)	
	1	2	3	4	5	6	7	8	9
Flow rate (l d^{-1})	60	60	40	40	40	60	60	40	40
HLR (m^3 m^{-2} ·d^{-1})	5. 31	5. 31	3. 54	3. 54	3. 54	5. 31	5. 31	3. 54	3. 54
OLR (kg BOD m^{-3}·d^{-1})	0. 268	0. 268	0. 282	0. 294	0. 301	0. 422	0. 432	0. 437	0. 443
NLR (g NH_4-N m^{-3}·d^{-1})	72. 7	73. 6	78. 3	80. 6	76	119. 3	111. 5	120. 2	126. 1
Recirculation (%)	0	100	0	100	200	0	100	0	100

NLR: Nitrogen volumetric loading rate HLR: Hydraulic lolading rate, OLR: Organic loading rate

Table 3. Typical design information for trickling filters [19-20]

Item	Low-rate	Intermediate rate	High rate	Super high rate
Filter media	Rock, slag	Rock, slag	Rock	Plastic
HLR ($m^3 m^{-2} \cdot d^{-1}$)	1.17-3.52	3.52-9.39	9.39-37.55	11.73-70.41
OLR (kg BOD $m^{-3} \cdot d^{-1}$)	0.08-0.40	0.24-0.48	0.48-0.96	0.48-1.6
Depth (m)	1.83-2.44	1.83-2.44	0.91-1.83	3.05-12.19
Recirculation ratio (%)	0	0-100	1-200	1-200
Filter flies	Many	Some	Few	Few or none
Sloughing	Intermittent	Intermittent	Continuous	Continuous
BOD removal (%)	80-90	50-70	65-85	65-80
Effluent	Well nitrified	Partially nitrified	Little nitrification	No nitrification

HLR: Hydraulic loading rate, OLR: Organic loading rate

Table 4. Characteristics of incoming wastewater

	Case 1		Case 2		Case 3	
	Range	Average	Range	Average	Range	Average
pH	7. 6-8. 1	7. 9	7. 3-8. 3	7. 8	7. 8-8. 4	8. 0
Alkalinity (mg l^{-1})	176-220	190.6	259-293	274. 5	365-422	393. 9
COD (mg O_2 l^{-1})	126-153	140. 9	183-214	196. 5	266-299	282. 5
BOD (mg O_2 l^{-1})	69-93	81. 0	113-141	127. 4	176-219	197. 5
SS (mg l^{-1})	52-73	63. 5	50-82	67. 5	49-85	68. 8
TKN (mg l^{-1})	23. 1-28. 4	25. 5	36. 3-42. 6	39. 5	52. 8-64. 5	59. 1
NH_4-N (mg l^{-1})	18.0-24.3	21.8	33.1-37.4	35.3	48.2-62.0	53.9
NO_3-N (mg l^{-1})	0.0-0.4	0.1	0.0-0.7	0.1	0.0-0.3	0.1
P (mg l^{-1})	2.8-3.6	3.2	4.6-5.8	5.3	6.8-8.9	7.9

Experimental conditions for this study are summarized in Table 2. Domestic wastewater of low strength with BOD ranging from 50-60 mgl^{-1} was used after increasing its BOD and NH_4-N to the desired influent concentration. For this purpose, glucose and NH_4Cl were added. Three cases having influent BOD of nearly 80, 130, and 200 mgl^{-1} were fed. The present system of the slag media trickling filter can be classified as an intermediate-rate system due to parameters such as hydraulic and organic loading rates, as described in Table 3. The recirculation ratio was varied from 0 to 2 for the additional removal of organics and nitrogen in the slag media trickling filter. The trickling filter throughout these studies was operated in a temperature-controlled room maintained at 20 °C. The characteristics of the incoming wastewater are presented in Table 4. Standard methods [18] were employed for all analyses.

Conclusions

This paper indicates that about 80% BOD and 70% NH_4-N removal efficiencies were achieved at 0.44 kg BOD $m^{-3} \cdot d^{-1}$ loading rate. Improved organic and ammonia removal was recorded in the effluent recirculation modes. Effluent recirculation improved the removal efficiency of BOD and NH_4-N by a further 5.3-9.9% and 3.4-16.5% respectively, compared to that in the non-recirculation modes. The results confirm that a BOD of less than half is needed to remove a unit amount of nitrogen in comparison to that in biological nutrient removal processes.

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