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Treatment of a polluted stream by a fixed-bed biofilm reactor with sludge discharger and backwashing system

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Abstract

A fixed-bed biofilm reactor with sludge discharger and backwashing system was used as an on-site pilot facility to treat polluted stream water. The annual mean influent concentrations of biochemical oxygen demand (BOD) and total suspended solid (TSS) were 73.9 and 81.5 mg/l, and the removal efficiencies were 87.3 and 86.8%, respectively. The sludge discharger and backwashing system periodically removes influent TSS and excess biofilm, and maintains a constant effluent concentration (BOD: 6–10 mg/l, TSS: 5–11 mg/l). Overall, this system has the potential for long-term water quality improvement of polluted streams without bed clogging.

Keywords: Polluted stream; Fixed-bed biofilm reactor; Ceramic media; Backwashing; Sludge discharger

1. Introduction

There is considerable worldwide concern about the deterioration of water quality in public areas. In Korea, the Ministry of Environment started River Purification Works in 1987 as a management program for non-point-source and river environments. This program includes water purification and natural recovery by physical methods. By 2000, it was carried out in 42 rivers. By these efforts, the water quality of main streams or rivers flowing through cities has been improved [1]. However, in regions where there are insufficient wastewater treatment plants, for example in rural or small communities, most small streams have been highly polluted by a variety of non-point-source contaminants from agricultural and domestic wastewater, by point-source contaminants from domestic and industrial wastewater, and in some cases even by untreated sewage [2].

Onsite purification processes to treat small streams or lakes and marshes include lagoons, capillary-seepage trench systems, constructed wetlands and biofilm processes, among others [3–5]. The capillary-seepage trench system has several advantages; however, it is limited by the soil-clogging problem and the contamination of underground water and soil. Lagoons and constructed wetlands are restricted in their application because they require large sites; moreover, the treatment efficiency of constructed wetlands decrease due to the death of aquatic plants in the winter season [6]. Among the onsite purification processes for small streams, the fixed-bed biofilm process using gravel as support media has been generally applied in Japan and Korea because it has several advantages such as low construction and maintenance costs [2].

The fixed-bed biofilm process for small streams, developed and used in Japan, had horizontal flow and did not have a sludge chamber, so sludge accumulated in the front of the reactor. In the system applied in Korea, sludge chambers for sludge storage were installed on the bottom of the reactor to prevent the bed from clogging with influent suspended solids [7]. Nevertheless, as the sludge accumulation time passed over 17 months, problems caused by long-term sludge storage, such as anaerobic condition of the reactor and sludge outflow, arose [8].

A fixed-bed biofilm process using ceramic media and applied to a highly polluted stream, was investigated in this study. The system was easy to maintain, and solved the problem of bed clogging by changing the influent flow pattern from horizontal to vertical, and by employing a sludge chamber on the bottom of reactor with a sludge discharger and backwashing system. A short account of the design and

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construction of the pilot-plant, and the first results of the process, are given in this paper.

2. Materials and methods

2.1. Principle of sludge discharger, and batch experiments with sludge discharger and airlift pump

The sludge discharger used in this experiment has been improved from the conventional airlift pump. The main principle of the sludge discharger is similar to that of Kando's invention [9] and the Geyser pump [10], but the shape was changed. Detailed principles, the operational procedure and the difference from the conventional airlift pump were well shown in Kando's study [9].

Schematic diagrams of the sludge discharger and the conventional airlift pump are compared in Fig. 1. The sludge discharger is composed of a discharge pipe, air chamber, air effluent halls and input air-line, whereas the conventional airlift pump is composed of a discharge pipe and input air-line. The air chamber in the sludge discharger is composed of a space between the inside and outside wall and a space between the inside wall and the discharge pipe, and effectively serves as an air tank. The discharge pipe is mounted in the center of the air chamber, having an open upper end, air effluent halls and an intake port at the lower end.

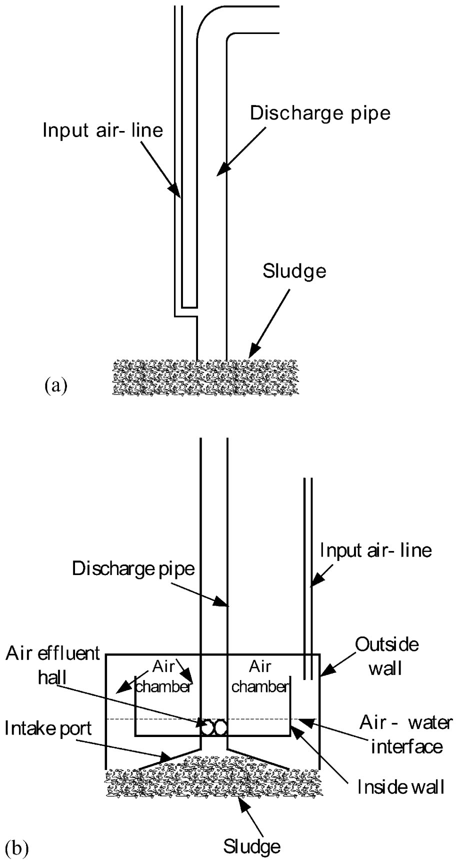


Fig. 1. Schematic diagram of the conventional airlift pump and sludge discharger: (a) airlift pump, (b) sludge discharger.

In operation, air accumulates in the air chamber and forces liquid down within the air chamber until it reaches the air–water interface of the air effluent halls in the discharge pipe, and a mixture of liquid and air is discharged as a powerful burst of aerated liquid from the upper end of the discharge pipe. The system recycles automatically after each burst of aerated liquid [9].

Experiments on discharge pressure using tap water with the sludge discharger and airlift pump were conducted on different discharge pipe diameters and airflow rates at a water level of 100 cm and a running time of 2 min. The inside and outside wall of the sludge discharger was 140 and 160 mm, respectively. A pressure gage was installed at the end of the discharge pipe.

Sludge discharging experiments were conducted using of a sludge discharger and an airlift pump of the same diameter of discharge pipe (25 mm) with digested sludge of a total suspended solid (TSS) concentration of 19 023 mg/l from a municipal wastewater treatment plant, in order to determine the sludge discharging performance of the sludge discharger and airlift pump.

2.2. Reactor system and ceramic media

The treatment system consisted of a reservoir tank (0.66 m^3) and a fixed-bed biofilm reactor of pilot scale (Fig. 2). The fixed-bed biofilm reactor had a total volume of 1.0 m^3 (500 mm × 1350 mm × 1500 mm) and consisted of an inlet port (0.1 m^3), an effective reaction volume (0.6 m^3) and a sludge chamber (0.3 m^3) on the bottom of the reactor. Five baffles were installed on the top of the sludge chamber to prevent the rising of accumulated sludge. For aeration and backwashing, four diffusers were installed on the bottom of the reactor.

The support media were ceramic (length: 25 mm, outside diameter: 25 mm, inside diameter: 17 mm) and were developed by Seobong Co. in Korea. The ceramic media were made of loess, fly ash and a foaming agent (coal).

2.3. Continuous sludge discharging and backwashing

The sludge discharger (diameter of discharge pipe: 30 mm, outside-wall diameter of air chamber: 200 mm) was installed on the bottom of the reactor and the accumulated sludge was discharged periodically by a supply of air (10 l/min). Excess biological sludge attached to the ceramic media was removed from the media by the backwashing system. Backwashing was continued for 60 min (11 am) with air (60 l/min) and influent stream water.

2.4. Reactor operation

Polluted stream water was supplied from a nearby small stream at Catholic University of Busan in Korea; it was

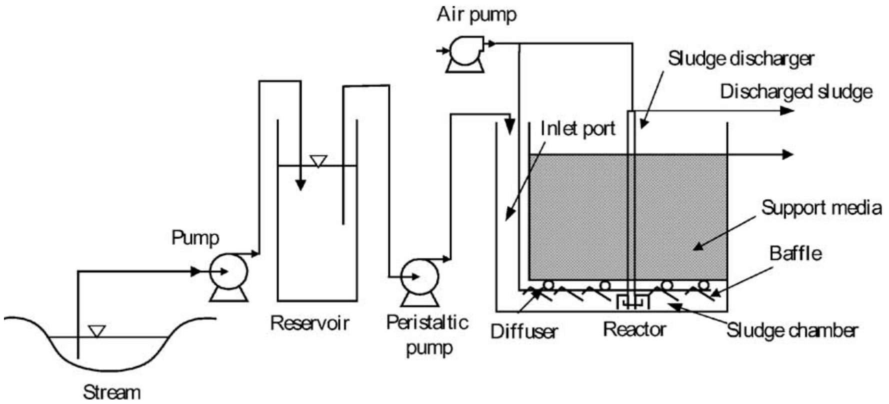


Fig. 2. Schematic diagram of the reactor system.

composed of sewage, restaurant effluent, rainfall and sanitary sewage. Stream water was collected into the reservoir and driven to the inlet port of the reactor with a peristaltic pump. The fixed-bed biofilm rector was inoculated with activated sludge (TSS concentration: 5000 mg/l, volatile suspended solid (VSS) concentration: 3510 mg/l) from a municipal wastewater treatment plant.

Samples were taken from 8 am to 8 pm with 2-h interval a day. The collected samples were calculated based on flow-weighted average concentration. Hydraulic retention time (HRT) of reactor was fixed at 6 h in order to introduce the settling of the influent TSS on the bottom of the reactor. Inlet airflow rate for aeration was fixed at 20 l/min (except backwashing). The operation periods were 360 days (June 6, 2001 to May 31, 2002).

2.5. Chemical analysis

The following parameters were determined: biological oxygen demand (BOD) and TSS. These parameters were analyzed according to standard methods [11]. The amount of discharged sludge through the sludge discharger or airlift pump and the backwashed sludge amounts in batch and continuous experiments were calculated by TSS concentration and volume.

3. Results and discussion

3.1. Comparison between sludge discharger and airlift pump

In order to evaluate the application of sludge discharger to the removal of the accumulated TSS from the bottom of the reactor, a comparison of the performances of the sludge discharger and the conventional airlift pump was conducted. Table 1 shows the discharge pressures of the discharges. Under the conditions of a large diameter of discharge pipe and a low airflow rate, the discharge pressure in the airlift pump was 0 mmH_2O, and water could not be discharged. However, water could be discharged from the sludge discharger because of the characteristics of the apparatus, which collects air in the air chamber. The discharge pressure was increased with an increase of airflow rate and a decrease of the diameter of the discharge pipe, for both the sludge discharger and the airlift pump. The discharge pressures of the sludge discharger were 3–6 times higher than those of the airlift pump. Accordingly, we can see that the operational range of the sludge discharger was broader than that of the airlift pump and the discharge pressure of the sludge discharger was more powerful than that of the airlift pump.

Table 1
Comparison of sludge discharger and airlift pump on discharge pressure

Discharge pipe (mm)	Airflow rate (l/min)	Discharge pressure (mmH_2O)	
		Sludge discharger	Airlift pump
50	2.5	60	0
	5.0	60	0
	7.5	60	20
	10.0	80	20
40	2.5	100	0
	5.0	100	20
	7.5	120	30
	10.0	120	30
25	2.5	140	30
	5.0	180	30
	7.5	220	40
	10.0	240	50

Table 2 shows the results when the reactor was operated under the conditions of an airflow rate of 10 l/min

Table 2
Comparison of sludge discharger and airlift pump on discharge of digested sludge

Items	Sludge discharger	Airlift pump
Initial sludge concentration (mg/l)	19 023	19 023
Effluent TSS concentration (mg/l)	12 500	3872
Effluent volume (l)	7.2	16.8
Total effluent TSS amount (g)	45	32
Dischage pressure (mm H_2O)	210	40

and a running time of 2 min. The effluent volume of the airlift pump was 2.3 times higher than that of the sludge discharger because the operational mode of airlift pump is continuous but that of the sludge discharger is discontinuous [10]. However, the concentration of discharged sludge and total effluent TSS amount from the sludge discharger were 3.2 times and 1.4 times higher than those of the airlift pump, respectively. This result may result from the difference of discharge area. The discharge area of the sludge discharger (i.e. the area of the intake port: 113.1 cm^2) was much larger than that of the airlift pump (area of discharge pipe: 4.9 cm^2). The reason for the low discharge concentration from the airlift pump was that a small amount of concentrated sludge around the discharge pipe was discharged first, followed by the discharge of sludge diluted by water, because of the narrow discharge area. In addition, the discharge pressure of the sludge discharger was 5.3 times higher than that of the airlift pump. Therefore, we can see that the sludge discharger was superior to the airlift pump in overall performance and in the extraction of sludge.

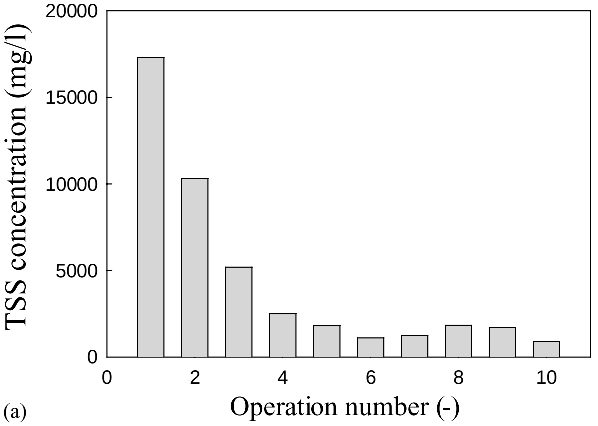
3.2. *Continuous sludge discharge and backwashing*

Continuous sludge discharge and backwashing was conducted with the fixed-bed biofilm reactor as shown in Fig. 2. To observe the accumulated sludge, the bottom of the reactor was monitored periodically *by visual inspection*. The sludge discharge experiment was begun after 107 days because of the low influent TSS concentration of the earlier period.

In order to determine the optimum operating time for the sludge discharger, the accumulated sludge was discharged at an airflow rate of 10 l/min, for 2 min per operation. The discharged TSS concentration with the operation number is shown in Fig. 3(a). The initial TSS concentration at the first operation was 17 290 mg/l, exponentially decreasing with the operation number, it was 1100 mg/l at the sixth operation. After the sixth operation, the discharged TSS concentration remained constant. After this experiment, we can see that the optimum number of operations for sludge discharge was six or seven times (12 or 14 min).

The total amount of discharged sludge for all experimental periods is shown in Fig. 3(b). The behavior of the discharged sludge was similar to that of the influent BOD and TSS. The initial discharged amount over the first discharging period was 349.4 g, because the TSS accumulated for 105 days. The discharged sludge volume remained at 9–10 l regardless of seasonal variation or operating interval (data not shown). The VSS/TSS ratio of the discharged sludge ranged from 0.32 to 0.36, which indicated that most of the accumulated sludge was inorganic material.

Although the accumulated TSS on the bottom of the reactor was not discharged thoroughly with one operation over 14 min, the control of the accumulated sludge on the bottom of reactor was possible by periodical operation (about once a month) using the sludge discharger.



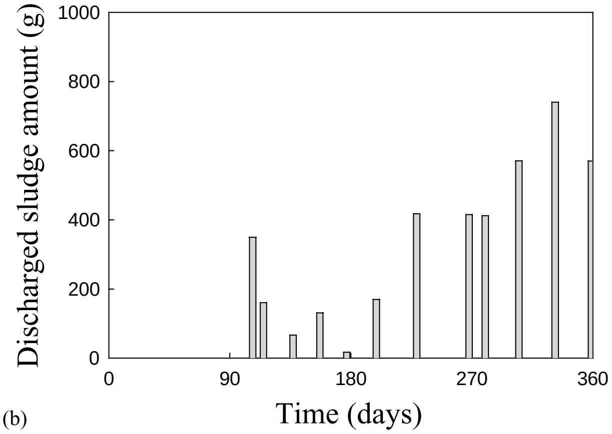


Fig. 3. Variation of TSS concentration and discharged sludge amount on time course with sludge discharger: (a) TSS concentration at one operation, (b) discharged sludge amount.

When the effluent BOD or TSS concentration rose over the mean concentration within a week, backwashing started. Backwashing began after 199 days because of the low BOD and TSS loading rates earlier. The first and second backwashed sludge amounts were 264.7 and 141.2 g, respectively; subsequent backwashed sludge amounts increased, and were within the range of 421.0–524.0 g (Fig. 4).

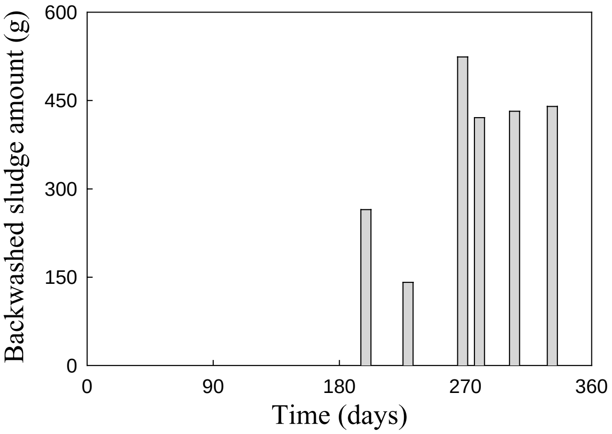


Fig. 4. Bachwashed sludge amount on time course.

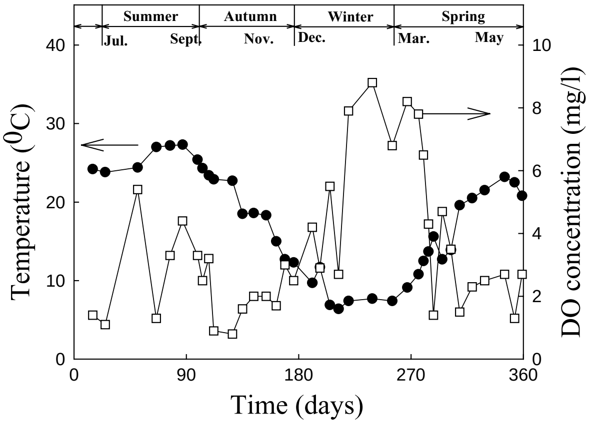


Fig. 5. Variation of temperature and DO concentration on operating time.

The VSS/TSS ratio of the backwashed sludge ranged from 0.83 to 0.85 over all operational periods. Therefore, the backwashed sludge was considered organic material which was caused by the detachment of excess biofilm. It was considered that influent TSS, which is composed of inorganic material, was not introduced into the media layer, because influent TSS settled in the sludge chamber on the bottom of the reactor by the vertical flow of the inlet port. In addition, the baffles prevented the accumulated TSS on the bottom of the reactor from rising. After backwashing, the effluent BOD and TSS concentration reached the mean concentration within 3 days.

3.3. BOD, TSS removal

Fig. 5 shows the day-mean temperature and dissolved oxygen (DO) concentration of the influent during the experimental periods. The arithmetic mean values were calculated by averaging the influent values. The temperature varied with seasonal change, whereas DO concentration changed with season and rain. The temperature variation with the change of season from summer to winter was about 20 °C, and the variation of DO concentration ranged from 2 to 6 mg/l.

Fig. 6 shows the day-mean BOD and TSS concentration of the influent and effluent during the experimental periods. The influent concentrations of BOD and TSS in late spring and summer were lower than those in other seasons because of the frequent rain in late spring and the rainy season of summer (50–112 days). The influent BOD concentration ranged from 15.2 to 132.6 mg/l and the annual mean influent BOD concentration and that in late spring and summer were 73.9 and 17.5 mg/l, respectively. Although the influent BOD concentration, DO concentration and temperature varied with season and rain, BOD removal efficiency in this study was maintained at a high and constant rate (removal efficiency: 85.4–93.3%, effluent BOD concentration: 6–10 mg/l).

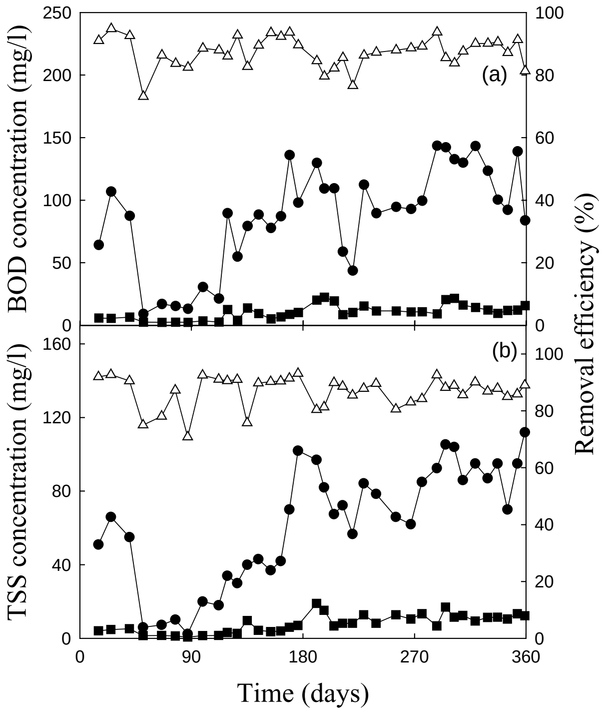


Fig. 6. Variation of influent (●), effluent (■) and removal efficiency (△) of (a) BOD and (b) TSS on operating time.

Table 3 shows the experimental conditions and results of this study and of other researcher's efforts to treat streams using a fixed-bed biofilm reactor. When compared according to BOD loading rate, the BOD removal efficiency in this study was higher than that of Lim [12], Choi [14] or Park [15] and similar to that of Kim et al. [16].

As shown in Table 3, the existence of a sludge discharging system and periodical removal of accumulated sludge had an important role in BOD removal. It was considered that the periodical removal of influent TSS and excess biomass by the sludge discharger and backwashing system might maintain a constant biomass and DO concentration (4–6 mg/l) during the experimental periods (data not shown). Therefore, a high removal efficiency and constant effluent BOD concentration was possible in spite of the variation of operating conditions.

The behavior of the influent TSS concentration was similar to that of influent BOD. The influent TSS concentration ranged from 8.5 to 110.5 mg/l, and the mean TSS concentrations for the year and the rainy season were 81.5 and 15.0 mg/l, respectively. Even though the influent TSS concentration fluctuated by rain, the average effluent TSS concentration in all seasons was almost constant, falling in the range of 5–11 mg/l.

Although a clarifier was not installed in the reactor, the TSS removal efficiency was higher than that of the others results, as shown in Table 3 [12–15]. Kim et al. [16] reported that a settling tank and facility for sludge settling was necessary for a higher TSS removal efficiency in stream purification systems. However, judging from the results of this study and others, the periodical removal of accumulated sludge is more important to BOD and TSS removal.

Table 3
Comparison of experimental conditions and results between this study and other’s

	Waste water	Media	BOD			TSS			Existence of sludge storage, discharging, clarifier and backwashing system			
			Mean concentration (mg/l)	Loading rate (kg BOD/m^3/day)	Removal efficiency (%)	Mean concentration (mg/l)	Loading rate (kg SS/m^3/day)	Removal efficiency (%)	Sludge chamber	Sludge discharging system and discharging period	Clarifier	Backwashing
This study	Stream water	Ceramic	73.9	0.296	87.3	81.5	0.326	86.8	○	○ (Sludge discharger) periodical	×	○
Lim [12]	Stream water	Gravel	8.2	0.103	50.7	10.8	0.136	49.0	○	× Intermittent	○	×
Kim et al. [13]	Stream water	Plastic	15.9	0.254	91.5	8.75	0.14	74.8	○	○ (Airlift) periodical	○	×
Choi [14]	Stream water	Porous concrete	21.7	0.347	65.6	18.5	0.296	71.9	○	× Intermittent	○ (2 ea)	×
Park [15]	Stream water	String and used briquet	40.6	0.130	87.0	23.6	0.075	80.1	○	× Intermittent	○	×

The reason for the good TSS removal efficiency in this study could be considered to be the following: because the sludge chamber was installed on the bottom of the reactor, influent TSS accumulated on the bottom of the reactor; baffles were installed on the top of the sludge chamber and prevented the sludge from rising; settled sludge on the bottom of the reactor did removed periodically by the sludge discharger and so most of the influent TSS did not entered into the media layer. In addition, the excess biomass was removed by backwashing, and so most of the excess biomass did not outflow.

4. Conclusions

The fixed-bed biofilm reactor can be used to upgrade the water quality of polluted streams. The sludge discharger was superior to the conventional airlift pump in the aspects of operational range, concentration of discharged sludge and total amounts. The accumulated TSS on the bottom of the reactor was removed by the periodical operation of the sludge discharger, and the excess biofilm in the reactor was removed by backwashing. Although the influent concentration varied, the removal efficiency of BOD and TSS was maintained at over 86%. The optimum operational interval of sludge discharging with a backwashing was once a month. The fixed-bed biofilm reactor system using ceramic media and sludge discharging and backwashing system is an effective, attractive choice for the purification of polluted streams because of the high-efficiency removal of BOD and TSS, and the easy removal of accumulated sludge and excess biofilm.

Acknowledgements

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