

REMOVAL OF NITROGEN AND PHOSPHORUS IN BATCH REACTORS WITH FIBROUS PACKING

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Abstract

The sequencing-batch-reactor process, which has become popular in recent years, is effective for the removal of chemical oxygen demand (COD) from wastewater, but requires external carbon for the effective removal of nitrogen. A dual-reactor system operated in sequencing-batch mode was demonstrated in this study to be effective for the removal of not only COD but also nitrogen and phosphorus, without the addition of external carbon. Both reactors were packed with a fibrous medium with a high surface area and porosity. Using a personal computer with a programmable logic controller, the feed-and-draw sequence and aeration patterns were operated automatically. It was able to remove, on average, 89.9% of COD, 97.1% of $\text{NH}_3\text{-N}$, 97.3% of total-N and 75.2% of total-P from domestic wastewater at 24°C. The sludge yield was estimated as 0.22 g-VSS/g-COD removed.

Key words: Denitrification, fibrous packing, nitrification, nutrient, phosphorus, SBR, sequencing-batch reactor.

INTRODUCTION

In the past two decades, increasingly stringent regulations in many countries have demanded the removal of nitrogenous pollutants from municipal wastewater. Among the nitrogen-removal processes, the biological nitrification-denitrification process has become widely accepted for its reliability and low cost. In this process, nitrogenous pollutants are first converted into nitrate by the autotrophic nitrification bacteria under aerobic conditions. The nitrate is subsequently converted to nitrogen gas by the heterotrophic denitrification bacteria under anoxic conditions in the absence of free oxygen. During nitrification, the carbonaceous pollutants are also converted to carbon dioxide by the aerobic heterotrophic bacteria, leaving very little organic matter

behind for the subsequent denitrification. Thus, the lack of organic carbons often limits the denitrification efficiency (Narkis *et al.*, 1979; Skrinde & Bhagat, 1982). To overcome the carbon deficiency, an external organic C-source, such as methanol, is added to facilitate denitrification; however, it results in an extra operating cost.

Advanced treatment plants today are also capable of removing phosphorus from wastewater biologically. Levin and Shapiro (1965) were the first to notice that under anaerobic condition phosphorus would be released from the biomass, and Fuhs and Chen (1975) later identified *Acinetobacter* as the bacterium mostly responsible for the phosphorus removal. Although an obligate aerobe, *Acinetobacter*, however, under anaerobic conditions will sequester small organic substrates in the water through the cell membrane and store the organics as volutin granules of poly- β -hydroxybutyrate (PHB) (Nicholls & Osburn, 1979). The energy required is provided by the hydrolysis of polyphosphate within the cell. Phosphate, the hydrolysis product, is released through the cell membrane to the water. In the subsequent aeration, stored organics are metabolized, producing energy and allowing bacteria to take up the phosphate, which is again stored inside the cell as polyphosphate. Phosphorus is concentrated in the bacterial cells and removed from the system, along with the waste sludge.

A number of new biofilm reactors have been developed in recent years (Chen *et al.*, 1993). They seem to be able to maintain stable performance against hydraulic surges and shocks and have less chance of experiencing sludge bulking and bacterial foaming than the conventional activated-sludge process. Packing materials used in the past include stone, coke, ceramic materials, pall rings, plastic honeycomb and corrugated plastic sheets. Novel packing materials include ring lace (Iwai *et al.*, 1990; Lessel, 1991), net plates (Nambu *et al.*, 1991) and fibrous materials (Fang & Yeong, 1993; Fang *et al.*, 1993). In a study using a sequencing batch reactor (SBR) filled with fibrous packing materials, Fang *et*

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al. (1993) reported that the biomass grown on the fibre surface exhibited a high sequestration capacity for the soluble organics in the incoming wastewater.

The SBR technology has gained its popularity in the past decade mainly through the efforts of Irvine and his co-workers (Irvine & Busch, 1979). A conventional SBR is a batch reactor operated in four stages, i.e. fill, react, settle and draw, in sequence. It is easy to install and operate. Although it is effective for COD removal, an SBR cannot effectively remove nitrogen unless extra carbon is added for denitrification.

This study was conducted to study the effectiveness of a dual-reactor system with fibrous packing operated in SBR mode for nitrogen and phosphorus removal.

METHODS

Figure 1 illustrates the experimental set-up, which consisted of two 10-l cylindrical reactors made of Plexiglas with an internal diameter of 124 mm. A string of bundles of fibrous packing, as illustrated in Fig. 2, was affixed at the centre-line of the column. The bundles were evenly spaced at 60-mm intervals; each bundle was made of thousands of rayon fibres. Initially, settled sludge from a local activated-sludge plant was recirculated in the two reactors, allowing the biomass to become attached to the fibrous packing.

The dual-reactor system was operated in four separate stages, i.e. sequestration of organic matter from sewage, phosphorus release, nitrification/phosphorus-uptake and denitrification. The mode of operation in each reactor, the duration and the dissolved oxygen level at each stage are summarized in Table 1. Table 2 summarizes the average character-

istics of the settled sewage from the Tai Po Sewage Treatment Works, Hong Kong, used as the reactor influent throughout this study.

At Stage 1, settled sewage was fed into Reactor-D by pump P-1. Under anaerobic condition for 1 h, some of the organic matter in the sewage was sequestered by the biomass. Then, at Stage 2, the mixed liquor was pumped by P-2 to Reactor-N and was kept anaerobic for 30 min, allowing phosphorus to be released (Appeldoorn *et al.*, 1992). Reactor-N was then aerated at Stage 3 for 11.5 h to facilitate nitrification and phosphorus uptake. The mixed liquor was then pumped by P-3 to the holding tank while waiting to be transferred later. At this time, Reactor-D had already completed Stage 1 for the following batch. Mixed liquor of the following batch was thus pumped from Reactor-D to Reactor-N for

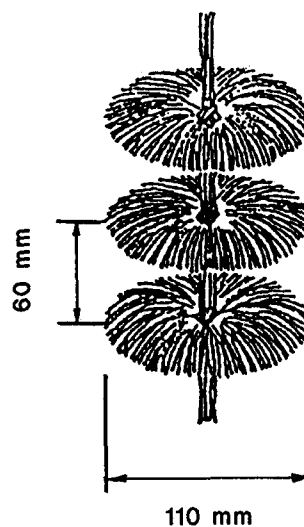


Fig. 2. Fibrous packing.

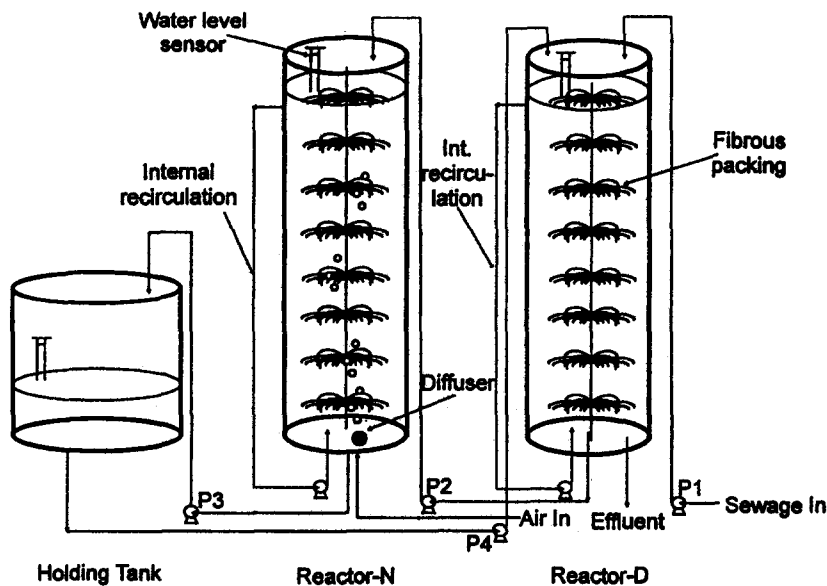


Fig. 1. Experimental set-up. See Methods for description.

Table 1. Mode of operation

	Stage 1	Stage 2	Stage 3	Stage 4
Reactor	D	N	N	D
Duration (h)	1.0	0.5	11.5	11
Dissolved oxygen (mg/l)	Nil	Nil	>4	<0.05
Reaction	Organic sequestration	P-release	Nitrification P-uptake	Denitrification

Table 2. Sewage composition

Sewage characteristics	Mean	Standard dev.
Temperature (°C)	24.0	0.8
pH	7.2	0.2
Total-COD (mg/l)	372	23
Soluble-COD (mg/l)	166	16
TSS (mg/l)	113	20
NH ₃ -N (mg/l)	47	6
TKN (mg/l)	55	10
Orthophosphate-P (mg/l)	6.3	0.5
Total-P (mg/l)	8.5	0.6

Stage 2 and 3 operations. The nitrified mixed liquor of the batch present in the holding tank was then pumped by P-4 to the empty Reactor-D for Stage 4 denitrification. After 11 h of denitrification, the mixed liquor was discharged as the final effluent. Reactor-D was then ready for another batch of operation.

Figure 3 illustrates the operation sequence and the conditions in both reactors at any moment. A personal computer equipped with a programmable logic controller was used to control all transfers of sewage or mixed liquor. Each transfer took less than 5 min. Beside these brief periods, both reactors were fully occupied at all times. As illustrated in Fig. 3, during the 12-h period when the mixed liquor stayed in Reactor-N for Stages 2 and 3, Reactor-D was conducting Stage 4 for the previous batch in the first 11 h and Stage 1 of the following batch in the twelfth hour. Thus, two batches were being treated at all times by the dual-reactor system. The overall hydraulic retention time for each batch was 24 h, based on the volume of a single reactor only.

After initial seeding of settled sludge, the system was operated continuously for 9 weeks with automatic control by the personal computer. After 4 weeks of acclimation, the system was assumed to have reached steady-state, judging from the steady COD in the effluent. The effluent quality was then closely monitored for 5 more weeks, during which COD and NH₃-N, of the effluent were measured daily, while total-N and total-P were measured once every other day. In three batches during the last week, COD, NH₃-N, nitrate-N and total-P of the mixed liquor at each of the four stages were closely monitored throughout the 24-h period.

RESULTS AND DISCUSSION

After 4 weeks of acclimation, the system performed satisfactorily. It consistently produced an effluent, on average over the 5-week period, containing 37 mg/l of soluble COD, 1.3 mg/l of NH₃-N, 1.5 mg/l of total-N and 2.1 mg/l of total-P, 89 mg/l of VSS and 113 mg/l of TSS. The corresponding removal efficiencies were 89.9% of soluble COD, 97.1% of NH₃-N, 97.3% of total-N and 75.2% of total-P. The SS in the effluent exhibited very good settleability; however, the removal of SS was not included in this study.

Figure 4(a) illustrates how the average soluble-COD of the mixed liquor varied throughout the four stages, while Fig. 4(b) illustrates the corresponding changes of NH₃-N, nitrate-N and total-P. At Stage 1, the incoming wastewater was first fed to Reactor-D and kept anaerobic for 1 h, during which time soluble COD was quickly decreased from 166 to 131 mg/l, indicating the sequestration of organic matter from the wastewater. The NH₃-N, nitrate-N and total-P remained unchanged in this period.

At Stage 2, the mixed liquor was transferred to Reactor-N and kept anaerobic for 30 min. The total-P in the mixed liquor increased from 7.5 to 32.4 mg/l, while the soluble COD was reduced from 131 to 101 mg/l but NH₃-N and nitrate-N remained unchanged. The increase of total-P was because bacteria hydrolyzed the polyphosphate within the cells to produce energy needed for the sequestration of soluble organics, and the hydrolyzed product, orthophosphate, was released from the cell to the mixed liquor. Figure 5 illustrates in more detail the correlation between the soluble COD reduction and the total-P released during Stage 2. The amount of soluble COD reduction was consistently 1.2 times the amount of phosphorus released. This ratio is comparable to the 1.38 observed by Iwewa and Meunier (1985), but higher than the 0.74 observed by Comau *et al.* (1985).

Figure 4 further illustrates that as aeration started at Stage 3, the soluble COD decreased quickly to 54 mg/l, within 1 h. Total-P decreased at a slower rate; about 4.1 mg/l/h over most of the period. The total-P was reduced from 32.4 mg/l gradually to 1.0 mg/l after 11.5 h of aeration. In contrast, the NH₃-N was reduced at a much faster rate than the increase of nitrate-N. The NH₃-N was reduced initially at a rate of 6.5 mg/l/h, presumably to form nitrate. However,

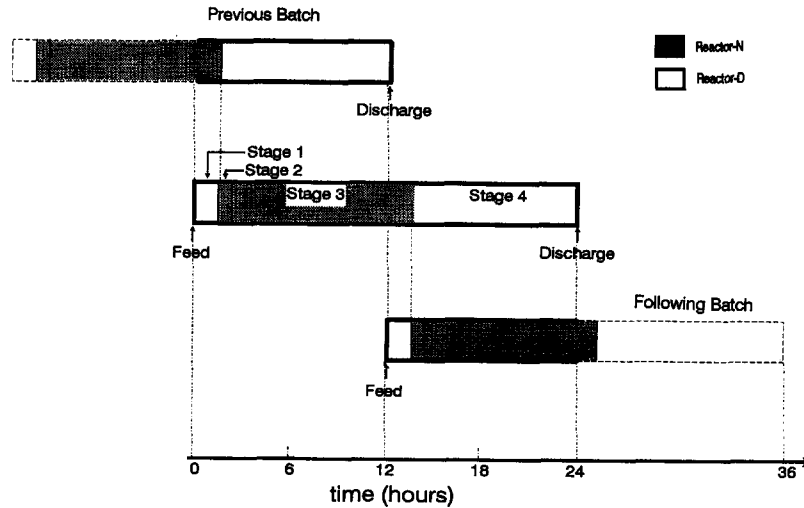


Fig. 3. Operation sequence and conditions in both reactors at any moment.

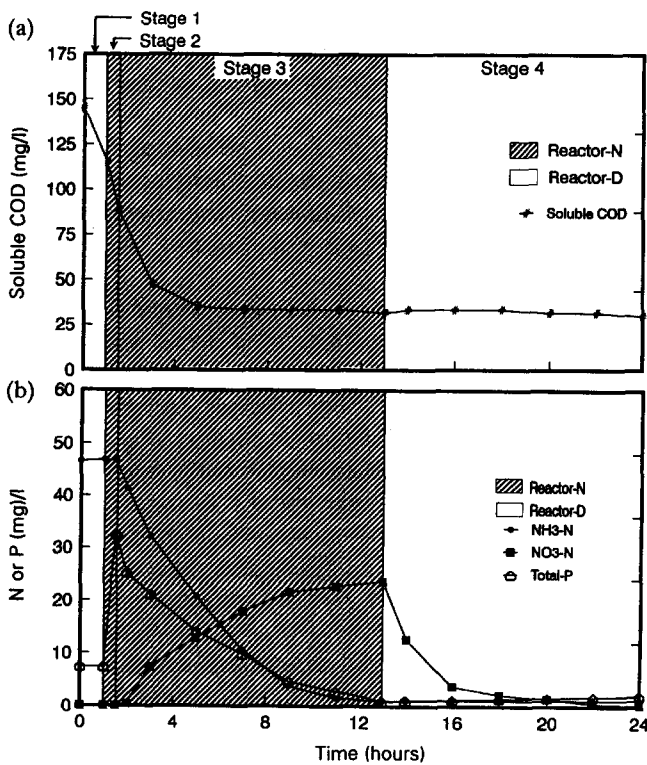


Fig. 4. Profiles of (a) soluble COD; (b) $\text{NH}_3\text{-N}$, nitrate-N and total-P.

the nitrate increased at a rate of only 3.2 mg/l/h. After 11.5 h of aeration, nitrate in the mixed liquor could only account for 51% of the $\text{NH}_3\text{-N}$ removal. Biomass in the reactor grew on the surface of the fibrous packing material forming 'biopomps'. The other 49% of the nitrate was believed to have been denitrified by bacteria inside the biopomps where the environment was anoxic (Fang & Yeong, 1993).

Figure 4 also illustrates that the final denitrification took place at Stage 4, during which the nitrate-N decreased from 23.7 mg/l to 3.8 mg/l in the first 4 h. Because the mixed liquor contained little

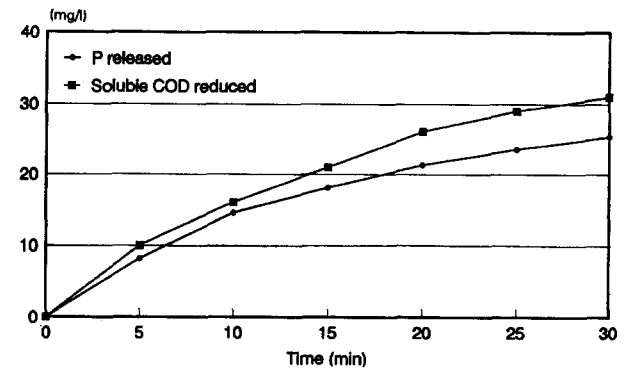


Fig. 5. Soluble COD reduced and phosphorus released in Stage 2.

soluble COD, the organic carbon needed for denitrification must have come from that sequestered by the biomass during Stage 1. Three additional hours were needed to reduce nitrate-N further to less than 2 mg/l.

Reactor-N was operated alternately under anaerobic and aerobic conditions to favour the growth of phosphorus-removing bacteria. The phosphorus content of its biomass averaged 8.4 g-P/g-VSS. Conversely, Reactor-D was never operated under aerobic conditions and, thus, was unfavourable for the growth of phosphorus-removing bacteria. The phosphorus content of its biomass averaged only 2.8 g-P/g-VSS. However, some of the phosphorus-removing bacteria were suspended in the mixed liquor of Reactor-N, and were carried over to Reactor-D during the transfer of mixed liquor. These bacteria released some phosphorus in Stage 4 when the nitrate became depleted in Reactor-D, resulting in a slight increase of total-P to 2.0 mg/l in the final effluent.

Based on the data of COD removal and VSS in the effluent, the sludge yield was estimated as 0.22 g-VSS/g-COD-removed.

CONCLUSION

Settled sewage was treated in a dual-reactor system under sequencing-batch mode, in which nitrification and denitrification were conducted separately. In one reactor, organic matter in the sewage was sequestered by the biomass and served as the carbon source needed for the denitrification to be carried out at the later stage. Another reactor was operated briefly under anaerobic conditions, followed by an extended period of aeration for luxury phosphorus uptake and for nitrification. The system was operated with the aid of a personal computer for automatic process control. It consistently removed 89.9% of COD, 97.1% of NH₃-N, 97.3% of total-N and 75.2% of total-P from settled sewage at 24°C without the addition of extra organic matter for denitrification.

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