# Development of a two-stage flexible fibre biofilm reactor for treatment of food processing wastewater

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**Abstract** Biofilm (or attached growth) reactors can be effectively used to treat organic wastewater from various industries such as food processing industry. They have a number of advantages including high organic loading rates (OLRs) and improved operational stability. A flexible fibre biofim reactor (FFBR) has been developed for efficient and cost effective treatment of food processing wastewater. In the process, simple flexible fibre packing with a very high specific surface area is used as support for microorganisms. The COD removal efficiencies for a range of OLRs have been studied. The FFBR can support an increasingly high OLR, but with a corresponding decrease in the COD removal efficiency. Therefore, a two-stage FFBR was developed to increase the treatment efficiency for systems with high OLRs. Experimental results indicated that a high overall COD removal efficiency could be achieved. At an influent COD of about 2700 mg/L and an OLR of 7.7 kgCOD/m$^3$d, COD removal efficiencies of 76% and 82% were achieved in the first and the second stage of the reactor, respectively. The overall COD removal efficiency was 96%. Therefore, even for wastewater samples with high organic strength, high quality treated effluents could be readily achieved by the use of multiple stage FFBRs.

**Keywords** Activated sludge process; attached growth reactor; biofilm reactor; flexible fibre packing; food processing wastewater; wastewater treatment

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## Introduction

Biological methods are commonly used in the treatment of organic wastewater. For example, the conventional activated sludge process (CASP) is usually used for the treatment of municipal wastewater around the world (Gray, 1990). In many cases, commercial and industrial wastewaters are also either directly discharged, or discharged after partial treatment, into the sewer and treated with the CASP. On the other hand, activated sludge processes are also extensively used for the treatment of various types of industrial wastewater (Eckenfelder and Musterman, 1995; Xu and Yu, 2000). However, there can be a number of problems in the treatment processes of the CASP. For example, the microorganisms in the aeration tank of the CASP cannot survive a continuous series shock loading and the process could become operationally unstable (Eckenfelder and Grau, 1998). High organic loading rates also typically leads to the problem of sludge bulking, in which the settling of the sludge from the effluent become difficult (Gray, 1990). This causes a dramatic reduction in treatment efficiency. Large amounts of sludge are produced and sludge handling and disposal is a major part of the wastewater treatment system (Vesilind *et al*., 2000).

Biofilm reactors (or attached growth reactors) can be used to avoid some of the above problems (Xu, 2001). In a biofilm reactor, the microorganisms are attached to an inert support material. The residence time of the sludge is usually long and the density of the microorganisms can be high. Therefore, they are much more resistant to various shock loads (Grady *et al*., 1999). The treatment efficiency can also be much improved. On the other hand, biofim reactors can be much more complicated in operation and may require high capital and operating costs. Some processes such as the rotating disk systems are generally not suitable for large-scale operations. Some other processes such as the packed bed and fluidised bed biological reactors may suffer from blockage problems (Grady *et al.*, 1999).

Recently, a flexible fibre biofilm reactor (FFBR) has been developed for the treatment of food processing wastewater (Xu, 2001; Xu *et al.*, 2001). In this reactor, packing that is made of flexible fibre was used. The fibre packing is a low cost material and provides a very high specific surface area (around 2200 $m^2/m^3$) for the attachment of microorganisms. The packing can be easily fixed into an existing reactor and it has a negligible pressure drop. The fibre in the packing is flexible such that it can provide limited movements that are induced by the flow of air and water. The movements avoid any blockage problems during the operation of the reactor. A comparative study with the CASP indicated that the FFBR has a number of advantages (Xu *et al.*, 2001). They include (a) high organic loading rates, (b) long sludge retention times and low sludge discharge rate in the settling tank (about 1/10th of CASP), (c) elimination of the sludge recycle stream, and (d) no sludge bulking problem at high organic loading rates. Therefore, the FFBR can provide a very efficient and cost effective treatment for food high strength organic wastewater.

The study also indicated that the FFBR can support an increasingly higher OLR, but with a corresponding decrease in the treatment efficiency. On the other hand, the amount of COD or BOD removed from wastewater increased with OLR, indicating higher productivities at high OLRs. To resolve this problem, a two-stage FFBR was developed to increase the treatment efficiency for systems with high OLRs. The first stage of the FFBR was operated at a high OLR to remove a high amount of COD, and the second stage was at a low OLR to produce a high quality effluent. Experiemntal results indicated that a high overall COD removal efficiency could be achieved. At an influent COD of 2700 mg/L and an OLR of 7.7 kgCOD/$m^3$d, COD removal efficiencies of 76% and 82% were achieved in the first and the second stage of the reactor, respectively. The overall COD removal efficiency was 96%. Therefore, even for wastewater samples with high organic strength, high quality treated effluents could be readily achieved by the use of multiple stage FFBRs.

## Materials and methods

### Wastewater and seed culture

Wastewater samples from the fruit and vegetable processing plants of Golden Circle Ltd, Brisbane, Australia were used in the experiments. The samples were taken from the wastewater effluent stream immediately after the dissolved air flotation tanks. The pH values of the wastewater ranged from 5.2 to 12.5 and were mostly on the alkaline side. The ratio of $BOD_5$ to COD was determined to be about 0.64, and the ranges of COD and $BOD_5$ were 5,400–9,800 $mg.L^{-1}$ and 3,300–6,300 $mg.L^{-1}$, respectively.

In the experiments, the wastewater samples were diluted by using tap water to produce the required influent COD values used in each experiment. The pH values of the influent wastewater were adjusted to the range of 6.5–8.5 by using 2 mol $l^{-1}$ sodium hydroxide (NaOH) and 36% hydrochloric acid (HCl). As the nutrient levels in the wastewater were low, nutrients were added in the influent equilibrium tanks according to a COD:N:P ratio of 100:2.5:0.5 for single-stage reactor experiments and 100:3.75:0.75 for two-stage reactor experiments. The nutrient compounds used were urea ($NH_2CONH_2$) and potassium dihydrogen orthophosphate ($KH_2PO_4$).

About 5 L initial seed culture for the sludge used in the reactor was collected from the Oxley Creek Wastewater Treatment Plant, Brisbane, Australia.

### Flexible fibre packing

Rayon fibres were bundled and circularly attached to a rope at intervals of about 80 mm.

The length of the fibre when straightened was about 75 mm and the diameter of the fibre was 0.07 mm. The rope was attached to a support frame and fixed vertically in the center of the reactor. The length of the rope inside the reactor was 885 mm and the attached fibre had a dry weight of 54 g. The packing had a specific contact surface area of around 2200 $m^2/m^3$ and a void fraction of more than 99%.



#### Biofilm reactor system

A laboratory scale FFBR system was set up with two reactors of identical configurations. A schematic diagram of a single reactor scheme is shown in Figure 1. For the two-stage reactor scheme, the two reactors were connected in series. The reactors have an internal dimension of 120 mm diameter × 900 mm height and an active volume of 10 L. Ceramic porous diffusers were installed at the bottom of the reactors for aeration. Two equilibrium tanks were used for storing influent wastewater, adjusting pH and adding nutrients. Two settling tanks were connected to the two reactors for separating the sludge from the effluent, a sludge recycle stream was found to be unnecessary and eliminated. This is a significant advantage of the FFBR processes.

#### Experimental

The reactor systems were operated continuously with fixed water flow rates (WFR) and air flow rates (AFR). In each experiment, the value of AFR was adjusted to ensure that the DO levels in the reactors were above 2 mg/L. The actual values of AFR, WFR and DO are given below in the results section. DO and pH values were monitored with meters and samples were taken daily for the analysis of influent and effluent. Standard methods were followed for analysis of all samples. All experiments were carried out at room temperature (22 ± 2°C). Further details of experimental procedures can be found in Xu (2001).

## Results and discussion

#### Single-stage reactor performance

A series of experiments with a single stage reactor was carried out to establish the relationship between the OLR and the COD removal efficiency and the COD removal rate of the FFBR. The experiments were carried out at a fixed hydraulic retention time and by increasing the influent COD from 360 to 2661 mg/L, with a corresponding OLR ranging from 1.04 to 7.66 $kgCOD/m^3d$. Detailed experimental conditions are given in Table 1 and the results are shown in Figures 2 and 3.

Linear relationships between OLR and COD (or BOD) removal efficiency (COD

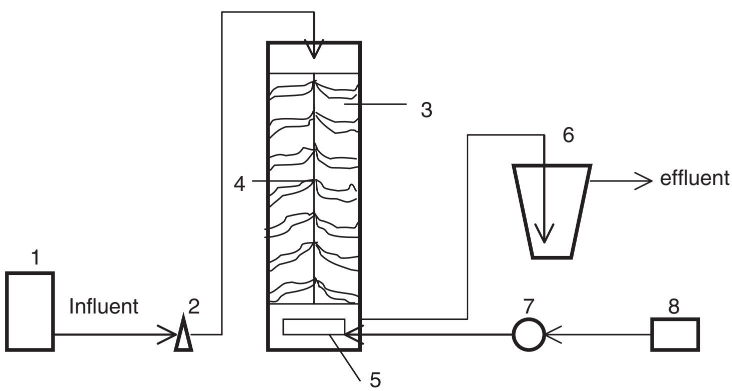


**Figure 1** Schematic diagram of a FFBR System (1: Equilibrium Tank, 2: Peristaltic Pump, 3: FFBR, 4: Fibre Packing, 5: Air Diffuser, 6: Settling Tank, 7: Air Flow Meter, 8: Air Compressor)

**Table 1** Conditions for single-stage reactor experiments

| Operating parameter | | | | | COD | | $BOD_5$ | |
|---|---|---|---|---|---|---|---|---|
| WFR (L/h) | AFR (L/h) | AFR/ WFR | HRT (h) | DO (mg/L) | Influent (mg/L) | OLR ($kgCOD/m^3d$) | Influent (mg/L) | OLR ($kgBOD_5/m^3d$) |
| 1.2 | 31.1 | 26 | 8 | 4.6 | 360 | 1.04 | 296 | 0.85 |
| 1.2 | 31.1 | 26 | 8 | 3.2 | 822 | 2.37 | 588 | 1.69 |
| 1.2 | 67.7 | 56 | 8 | 3.6 | 1142 | 3.29 | 790 | 2.28 |
| 1.2 | 190 | 159 | 8 | 3.5 | 2367 | 6.82 | 1,566 | 4.51 |
| 1.2 | 215 | 179 | 8 | 3.2 | 2661 | 7.66 | 1,752 | 5.05 |

WFR = water flow rate, AFR = air flow rate, HRT = hydraulic retention time

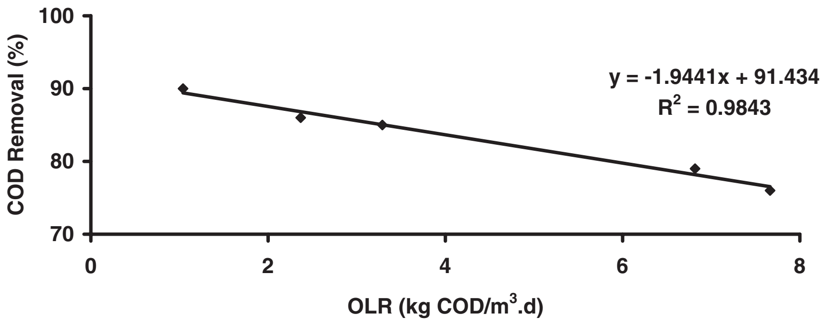


**Figure 2** Relationship between COD removal efficiency and OLR

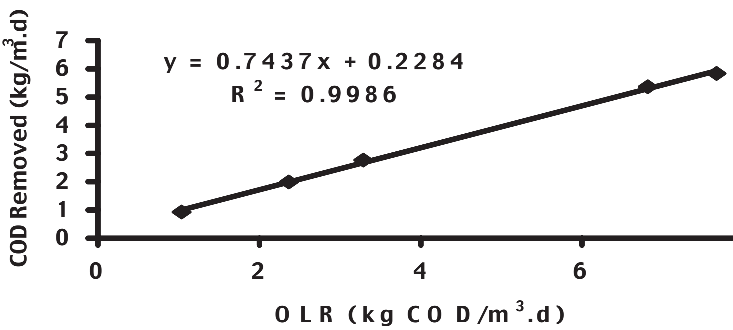


**Figure 3** Relationship between COD removal rate and OLR

removal), and OLR and COD removal rate (COD removed) were observed in the range of OLRs studied. In Figure 2, the COD removal efficiency decreased as OLR increased. At a low OLR of 1 $kgCODm^3d$, the COD removal efficiency was about 90%. Therefore, the COD in the effluent was about 36 mg/L and the quality of the effluent was high. On the other hand, at a high OLR of 8 $kgCODm^3d$, the COD removal efficiency was lower at about 75%, and the COD in the effluent was about 720 mg/L, for which further treatment may be necessary.

In Figure 3, the COD removal rate increased with OLR. This implies the productivity of the reactor, in terms of the amount of COD removed from wastewater, was higher when the reactor was operated with a higher OLR. Also, from Table 1, the air flow rate (AFR) required increased with OLR, as the amount of COD removed from the wastewater increased.

#### Two-stage reactor performance

From the performance data of the single-stage reactor in Figures 2 and 3, it can be seen that a high quality effluent could be obtained at a low OLR, while a high reactor productivity was achieved at a high OLR. Therefore, for the treatment of high strength wastewater, which usually leads to a high OLR, multiple stage reactors may be used to effectively obtain a high quality effluent. In this study, a set of experiments with a two-stage process was carried out to test the process. Detailed conditions of the experiments and the resultant performance parameters are listed in Table 2. The detailed histories of the influent and effluent COD, as well as the COD removal efficiencies, in each stage of the process are shown in Figures 4 and 5, as functions of time during the experiments. In the experiments, the average value of the influent COD was about 2,661 mg/L, with a corresponding organic loading rate of 7.66 kgCOD/m$^3$d. As can be seen from the results in Table 2 and Figures 4 and 5, a high quality effluent (with an effluent COD of 110 kgCOD/m$^3$d) can be achieved. The COD removal efficiencies in the first and the second stage of the reactor were about 76% and 82%, respectively, and the overall COD removal efficiency was about 96%. These results demonstrated that multiple stage FFBRs can provide much more effective treatment than single stage reactors for systems with high OLRs.



**Table 2** Conditions and performance parameters for two-stage reactor experiments

| Reactor stage | Stage 1 | Stage 2 | |
|---|---|---|---|
| Operating parameter | WFR (L/h) | 1.2 | 1.2 |
| | AFR (L/h) | 214.5 | 115.8 |
| | AFR/WFR | 179 | 97 |
| | HRT (h) | 8 | 8 |
| | DO in reactor (mg/L) | 2.7–5 | 3.6–5 |
| | DO in settling tank (mg/L) | 0.1–0.7 | 3.6–4.3 |
| | ORL (kgCODm$^3$d) | 7.66 | 1.83 |
| | ORL (kgBODm$^3$d) | 5.0 | 0.8 |
| Influent characteristics | COD (mg/L) (average value) | 2661 | 634 |
| | $BOD_5$ (mg/L) | 1752 | 269 |
| | pH | 4.6–8.2 | 7.6 |
| Effluent characteristics | COD (mg/L) (average value) | 634 | 110 |
| | $BOD_5$ (mg/L) | 269 | 27 |
| | pH | 7.6 | 8 |
| Sludge characteristics in liquid phase of FFBR | MLSS (mg/L) | 550–800 | 20–90 |
| | $SV_{30}$ (mg/L) | 0.1–0.7 | << 10 |
| | TS (%) | 0.2 | 0.1 |
| | TVS (%) | 62 | 30 |
| | TFS (%) | 38 | 70 |
| Removal efficiency | COD (%) | 76 | 82 |
| | $BOD_5$ (%) | 85 | 90 |
| Overall removal efficiency | COD (%) | 96 | |
| | $BOD_5$ (%) | 98 | |

WFR = water flow rate, AFR = air flow rate, HRT = hydraulic retention time

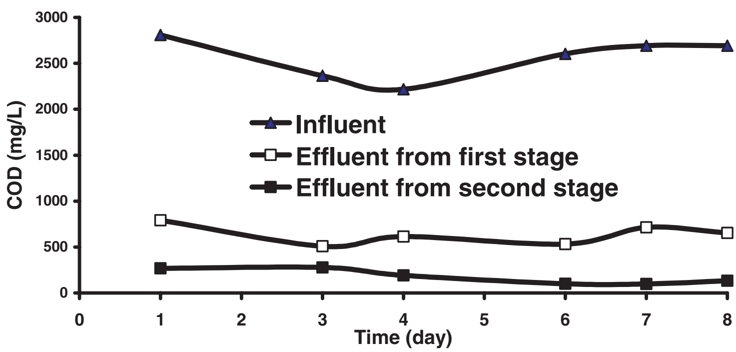


**Figure 4** Influent and effluent COD in two-stage reactor experiments

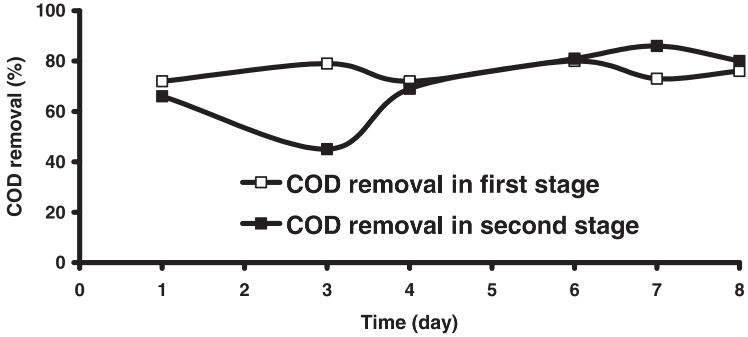


**Figure 5** COD removal efficiencies in two-stage reactor experiments

## Conclusion

A flexible fibre biofim reactor (FFBR) has been developed for effective treatment of food processing wastewater. The COD removal efficiencies for a range of OLRs have been studied and an inverse linear relationship between OLR and COD removal efficiency was observed. The FFBR can support an increasingly high OLR, but with a corresponding decrease in the COD removal efficiency. On the other hand, a linear relationship between OLR and COD removal rate was observed. The amount of COD removed from wastewater increased with OLR. To resolve this problem, a two-stage FFBR was developed to increase the treatment efficiency for systems with high OLRs. At an influent COD of about 2700 mg/L and an OLR of 7.7 kgCOD/m$^3$d, COD removal efficiencies of 76% and 82% were achieved in the first and the second stage of the reactor, respectively. The overall COD removal efficiency was 96%. Therefore, even for wastewater samples with high organic strength, high quality treated effluents could be readily achieved by the use of multiple stage FFBRs.

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