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Article

A Novel Fluidized Bed Reactor Configuration for Nitrate Reduction and Low Strength Anaerobic Wastewater Treatment

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Abstract. In this research, hydrodynamic behaviour in a novel fluidized bed reactor (FBR) was studied using a residence time distribution (RTD) experiment. The RTD experimental result showed that the liquid flow pattern closely resembled plug flow behaviour. This research utilized the novel FBR under low hydraulic retention time (HRT) operation (without internal recirculation), and thus the novel FBR's performance should be further investigated. Two wastewater treatment applications were studied in this research. The first application was to use the novel FBR for denitrification at COD:NO_3^- - N of 1:1, 2:1, 3:1, 5:1, and 10:1. The highest nitrate removal was obtained at a ratio of COD:NO_3^- - N of 3:1, with a removal efficiency of 99 ± 1%. The second application was to use the novel FBR for low strength anaerobic wastewater treatment. The novel FBR achieved 86 ± 6% of COD removal efficiency at an organic loading rate (OLR) of 5.6 g COD L^{-1} d^{-1}.

Keywords: Fluidized bed reactor, residence time distribution, wastewater treatment, denitrification, low strength anaerobic treatment.

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1. Introduction

Anaerobic reactors are widely used in wastewater treatment due to their low levels of energy consumption. Recovering energy from biological gases produced under anaerobic treatment and sludge digestion is more effective than aerobic treatment. Nowadays, many researches focus on the design of anaerobic reactors to achieve high substrate removal efficiency with low operating costs [1, 2]. An anaerobic fluidized bed reactor (FBR) is an attached growth wastewater treatment reactor which offers various advantages, such as high substrate removal efficiency due to enhanced contact between microbes adhered onto carrier media and wastewater stream, rapid recovery of stability with changes to operating conditions, and the ability to operate under low hydraulic retention times (HRT) due to the internal recirculation flow rate. However, one drawback of anaerobic FBRs is that they require a high up-flow velocity (because of recirculation) in order to fluidize the media bed, leading to higher reactor operation costs. The use of low density material as a supporting media may be an alternative way to conserve energy in conventional FBR.

In this research, a novel FBR configuration was developed using low density material as a media. Granular rubber is a low-density material, and has already been proven as an useable media in wastewater treatment systems. It is non-toxic for microorganisms in wastewater treatment under anoxic and anaerobic conditions [3]. A novel FBR can operate more effectively without internal recirculation, and therefor a recirculating pump is not required. However, the feeding flow rate must be increased to replace the recirculating flow rate. This leads to reactor operations with very low HRT. For biological treatment, the reactor configuration was modified by increasing the column height to prolong the reactor's HRT. These configurations lead to performance differences between the novel FBR from conventional FBR, which calls for investigation of the novel FBR's hydrodynamic behavior.

Among various experimental methodologies, residence time distribution (RTD) is widely used to describe the phenomenon and liquid flow pattern not only of chemical reactors but also of biological reactors [4-6]. The RTD measurement is an effective tool that can help understanding and determining hydrodynamic parameters [7]. Moreover, the RTD is a common interest in the study of hydrodynamic flow characteristics and dead volume in biological treatment reactors [8, 9]. Many researchers have studied the liquid flow pattern in reactors using RTD measurements. They have found different liquid flow patterns in different parts of the reactor, as described by RTD measurement [7, 10, 11]. In general, RTD measurements are acquired through tracer experiments and impulse response methods. Tracer injection occurs at the inlet of a reactor and an observation probe is located at the outlet. To interpret the RTD measurements, a flow model is selected to explain the liquid flow behavior of the reactor.

Even with the configuration made to increase HRT, due to a high up-flow velocity, novel FBRs are generally operated with a HRT of less than an hour. It has been reported that FBRs can achieve anaerobic treatment without internal recirculation [12], but the performance of this reactor must be investigated to prove its application for wastewater treatment, including anaerobic and denitrification processes.

For anaerobic treatment, HRT is an important factor in controlling the efficiency of the treatment system. Anaerobic treatment needs longer HRT than a biological denitrification process. Previous research has found that denitrification can occur in FBRs with HRTs of less than 30 minutes [13]. However, there are no reports of nitrate reduction in FBRs without internal recirculation that operated under a low HRT.

Therefore, there are two objectives of this current work. The first objective is to determine the hydrodynamic behaviour in a novel FBR at different flow rates. The second objective focuses on the performance of the novel FBR in wastewater treatment applications, including denitrification at different COD:NO_3^- - N ratios, and low strength wastewater treatment under anaerobic conditions.

2. Materials and Methods

2.1. Reactor Configuration and Operation

The FBR configuration described by Sirinukulwattana et. al [12] was adapted for denitrification process and low strength anaerobic wastewater treatment. The FBR was made of transparent plastic with 3 mm thickness, 0.03 m inner diameter, and 2.30 m column height. Granular rubber made from spent-tire waste was used as solid media. The rubber had a 0.43 mm average size, 1.2 g cm^{-3} density, 0.025 $m^2 g^{-1}$ specific surface area, and 1.53 uniformity coefficient. The upper part of the reactor was 0.35 m in height to prevent sludge back wash from the reactor and separated into three phases. The schematic diagram of the FBR is illustrated in Fig. 1.

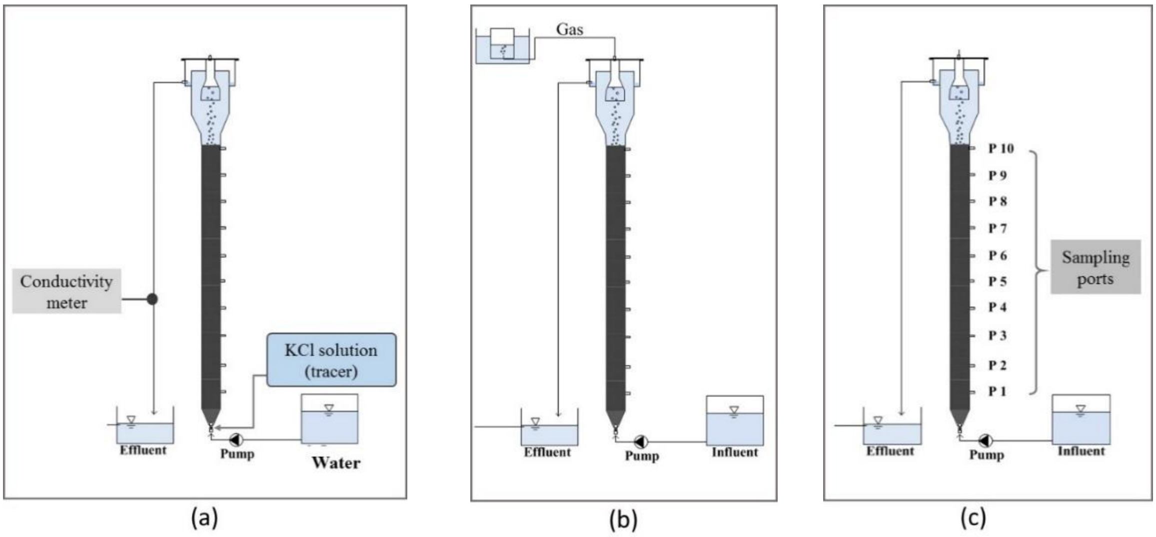


Fig. 1. Schematic diagram of a novel configuration fluidized bed reactor described for (a) RTD experiment, (b) performance of the reactor and (c) profiling of substrate removed.

Each novel FBR was seeded with 250 ml of seeding sludge from an anaerobic filter reactor, and then 1000 ml of granular rubber were added. The seeding sludge was collected from an anaerobic filter reactor at a wastewater treatment plant at the Faculty of Engineering, Chulalongkorn University. The total solids (TS) concentration of the seeding sludge was 8443 ± 588 mg L^{-1}.

In the denitrification experiment, wastewater with different COD:NO_3^- - N ratios were fed into the FBR. Nitrate and COD removal efficiencies were investigated under a low HRT of 50 minutes. Moreover, effluent pH and suspended solids were investigated. Nitrate nitrogen source was prepared from $NaNO_3$ with a fixed nitrate concentration of 100 mg L^{-1}. Varied COD concentrations using glucose (150, 250, 300, 500, and 1000 mg L^{-1}) were added to the synthetic wastewater corresponding to COD: NO_3^- -N ratios of 1:1, 2:1, 3:1, 5:1, and 10:1. The diagram of the reactor set-up is shown in Fig. 1(b).

To profile nitrate and COD-removal, liquid samples were taken from sampling ports. There were 10 sampling ports installed along the reactor height. The first sampling port P1 was located at 30 cm from the bottom of the reactor, and the distance between each subsequent port was 22 cm (As shown in Fig. 1(c)).

In the anaerobic experiment, a novel FBR was operated to remove organic carbon in wastewater. Table 2 shows overall experimental results from low-strength wastewater treatment at OLR of 5.6, 9.4, and 18.6 g COD L^{-1} d^{-1}. Different COD concentrations of wastewater were fed into the FBR as 481 ± 48 mg L^{-1}, 252 ± 39 mg L^{-1}, and 147 ± 19 mg L^{-1}, respectively. The diagram of the reactor set-up is shown in Fig. 1(b).

2.2. Experimental Determination of Residence Time Distribution (RTD)

The RTD experiments were examined at different water flow rates of 50 L d^{-1} (minimum flow rate), 60 L d^{-1} (average flow rate), and 70 L d^{-1} (maximum flow rate). A tracer (5 mL of 70 g L^{-1} KCl) was injected through the three-way port located at the inlet of the reactor. As shown in Fig. 1(a), the KCl concentration at the sampling port located by the exit port was measured as a function of time. Tracer concentration was measured by a conductivity probe (SevenGo Duo pro, METTLER TOLEDO, Switzerland).

The exit age distribution (E) was determined using the tracer method with a pulse regime, which is presented by the following Eq. (1) [14].

$$\int_0^\infty E\,dt = 1 \tag{1}$$

The variance of the curve and dead space in the reactor were calculated according to a model [14] as present in Eq. (2), Eq. (3), and Eq. (4).

Normalized mean: $$u_a = \frac{\int_0^\infty x \cdot \int(x)dx}{\int_0^\infty \int(x)dx} \quad (2)$$

Variance: $$\sigma^2 = \frac{\int_0^\infty (x-u_a)^2 \cdot \int(x) \cdot dx}{\int_0^\infty \int x \cdot dx} \quad (3)$$

Dead space: $$V_d = (1-v_a\mu_a) \cdot V \quad (4)$$

where V_d is the volume of dead space in the reactor (L), V is the theoretical working volume of the reactor (L), and v_a is the fraction of tracer.

2.3. Synthetic Wastewater Preparation

In this study, the synthetic wastewater was prepared from tap water using glucose as a carbon source. In the nitrate reduction experiment, the feeding solution contained different COD:NO_3^- - N ratios of 1:1, 2:1, 3:1, 5:1, and 10:1 mg COD L^{-1}. In the anaerobic treatment experiment, different COD concentrations in wastewater were varied at 150, 250, and 500 mg L^{-1}. Synthetic wastewater contained sufficient alkalinity and trace elements that are presented in Table 1.

Table 1. The compositions of synthetic wastewater in denitrification and anaerobic treatment.

Components	**Nitrate reduction at different COD : NO_3^- - N ratios**					**Low strength anaerobic wastewater treatment**		
	1:1	**2:1**	**3:1**	**5:1**	**10:1**	**COD 150 mg/L**	**COD 250 mg/L**	**COD 500 mg/L**
Glucose	0.13	0.23	0.40	0.57	1.15	0.15	0.25	0.50
$NaNO_3^-$ (g L^{-1})	0.61	0.61	0.61	0.61	0.61	-	-	-
$NaHCO_3$ (g L^{-1})	0.1	0.1	0.1	0.15	0.15	0.10	0.15	0.20
K_2HPO_4 (g L^{-1})	0.01	0.015	0.02	0.025	0.03	0.011	0.028	0.056
$MgSO_4.7H_2O$ (μg L^{-1})	400	400	400	400	400	400	400	400
$FeCl_2.4H_2O$ (μg L^{-1})	4	4	4	4	4	4	4	4
$CoCl_2.6H_2O$ (μg L^{-1})	1	1	1	1	1	1	1	1
EDTA (μg L^{-1})	10	10	10	10	10	10	10	10
$NiCl_2.6H_2O$ (μg L^{-1})	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
$MnCl_2.4H_2O$ (μg L^{-1})	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
$ZnCl_2$ (μg L^{-1})	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
$CaCl_2$ (μg L^{-1})	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
$CuCl_2.2H_2O$ (μg L^{-1})	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
$(NH_4)_6Mo_7O_4.4H_2O$ (μg L^{-1})	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Modified from [15] and [16].

2.4. Process Parameters

Before being subjected to chemical analysis, influent and effluent were filtered through glass micro-fiber filters (GF/C™, WATCHMAN™, UK). COD and total solids were measured according to the standard method for the examination of water and wastewater [17]. pH and conductivity were monitored by a pH meter (SevenGo Duo pro, METTLER TOLEDO, Switzerland). Nitrate concentration was analysed by an ion selective electrode (Seven Compact™ pH/Ion S220, METTLER TOLEDO, Switzerland). Volumes of biogas were collected from the effluent gas tube located on top of the reactor, with the composition of the biogas measured by a gas chromatograph.

3. Results and Discussion

3.1. Hydrodynamic Behavior in the Novel FBR

Three different water flow rates were studied: 50 L d^{-1}, 60 L d^{-1}, and 70 L d^{-1}. During RTD experiments, concentrations of tracer began to emerge in the effluent at 16 to 20 min after tracer injection. A high sharp peak of tracer was present at the exit age at around 32, 28, and 22 min, at water flow rates of 50, 60, and 70 L d^{-1}, respectively. The results from RTD experiments are shown in Fig. 2.

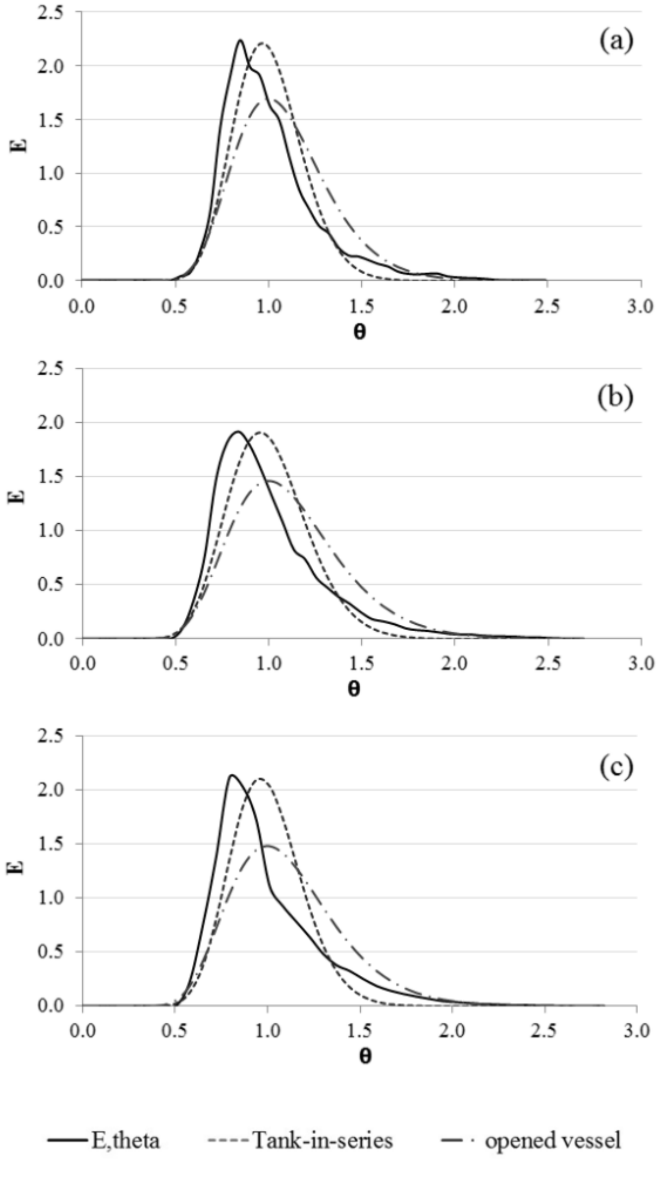


Fig. 2. The variation of experimental exit age distribution in a novel FBR at different flow rates: (a) 50 L d^{-1}; (b) 60 L d^{-1}; and (c) 70 L d^{-1}.

Figures 2(a), (b), and (c) illustrated experimental exit age with flow rates of 50, 60, and 70 L d^{-1}, respectively. It can be observed that the relations of E(t) at each flow rate were positively skewed distributions. According to the compartment model, this implied that the liquid flow pattern inside the reactor was mostly theoretical plug flow, with a little mixed flow behaviour also exhibited. About 12 – 17% of the total volume of the reactor exhibited mixed flow behaviour, as presented in Table 2. As flow rate increased, the proportion of the reactor exhibiting mixed flow behaviour also increased, similar to what is observed when recirculation is increased in other FBR. Mixed flow also implied that the liquid flow was more turbulent and resulted in an increase of the fluidization state.

Unlike the mixed flow volume, dead volume did not correlate to the liquid flow rate. At a flow rate of 70 L d^{-1}, 16.3% of the reactor became dead volume. This was higher than that at the flow rate of 60 L d^{-1}, which had the lowest dead volume of 13.1%, but lower than that at the flow rate of 50 L d^{-1}, which had the highest dead volume at 18.1%. Past hydrodynamic studies have observed 22% to 65% dead volume in FRB, depending on the volumetric flow rate [18]. Whereas in a high flow rate reactor study, dead volumes of 7.1% to 19.5% were exhibited by an expanded granular sludge bed (EGSB) at different flow velocities [19].

As illustrated in Fig. 2, the experimental graphs were close to the modified tank-in-series model. The results showed multiple equivalent CSTR tanks in each flow rate, meaning that liquid flow patterns in a novel FBR approached that of the plug flow reactor. The volume of plug flow regimes at each flow rate was in the range of 1.07 – 1.11 L, which made up the majority of the total reactor volume of 1.6 L. Conversely, only a small volume of mixed flow in the reactor was found.

Table 2. The condition and model analysis results of a novel configuration FBR.

Flow rate (L d^{-1})	**Design HRT (min)**	**Dead volume (L)**	**Plug flow volume (L)**	**Mixed flow volume (L)**
50	46.08	0.29 (18.1%)	1.11	0.20
60	38.40	0.21 (13.1%)	1.17	0.22
70	32.91	0.26 (16.3%)	1.07	0.27

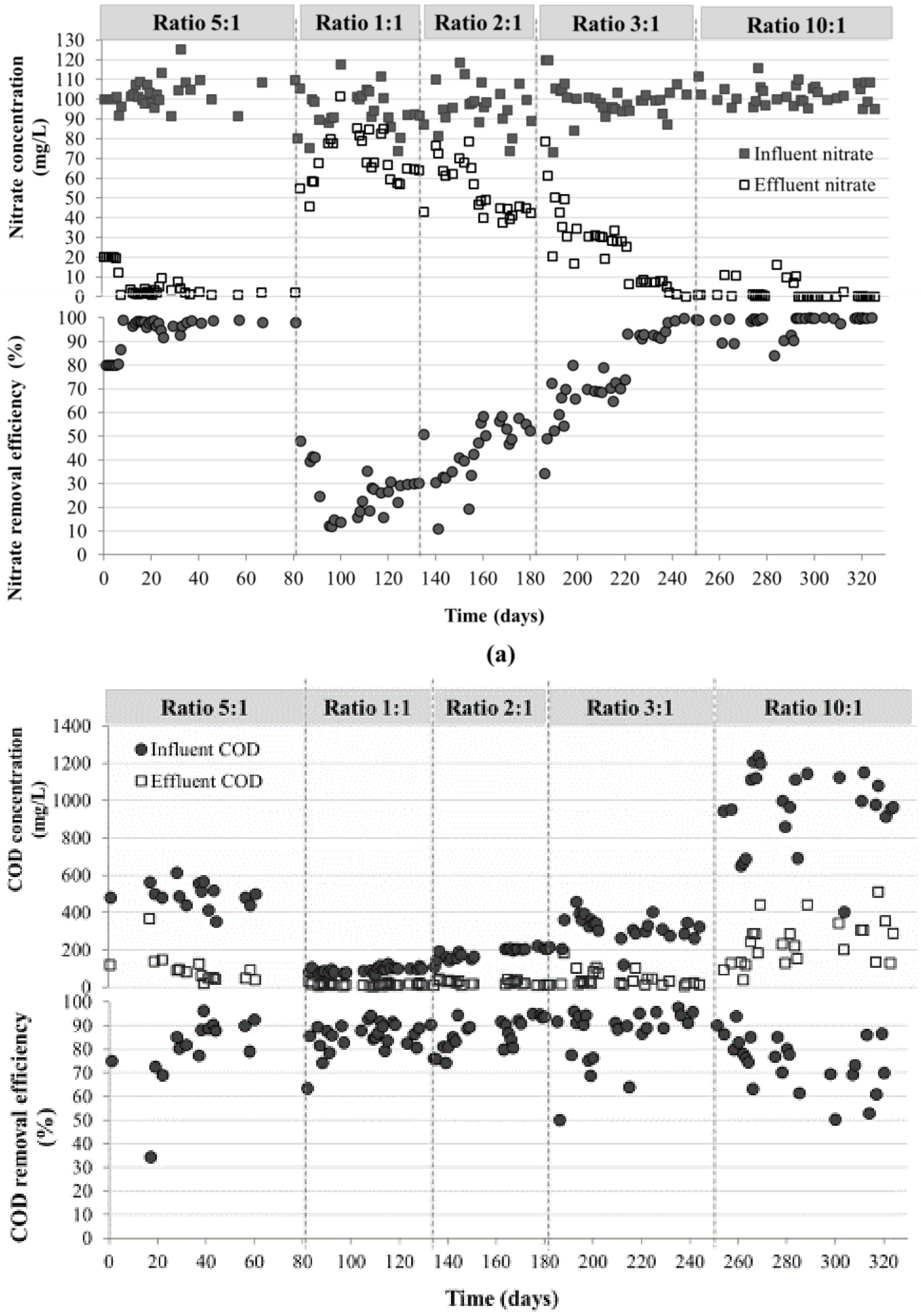
In previous research, there were reports of hydrodynamic behaviour in RTD experiments in a conventional FBR using light beads as a media. It was found that the liquid flow pattern was best described by a combination of plug flow and ideal mixing patterns [9].

From the overall results, it can be concluded that the hydrodynamics of liquid in a novel FBR was plug flow. The increase of liquid flow rate induced more mixed flow regime. At a flow rate of 60 L d^{-1}, the results showed the smallest volume of dead zone inside the reactor.

3.2. Performance of Nitrate Reduction in a Novel FBR

The novel FBR prepared with an initial COD:NO_3^- - N ratio of 5:1. After 60 days, the reactor reached steady state. Nitrate and COD removal efficiency were 99 ± 1% and 89 ± 5%, respectively. After the reactor achieved steady state, different COD:NO_3^--N ratios were fed to the reactor as 1:1, 2:1, 3:1, and 10:1. As illustrated in Fig. 3, it can be observed that different periods of time are required to reach steady state conditions at varied COD:NO_3^--N ratios. Low COD:NO_3^- - N ratios required longer periods to reach stead state than higher COD:NO_3^- - N ratios. Due to insufficient carbon sources at low ratios of COD:NO_3^- - N at 1:1 and 2:1, the results show low nitrate removal efficiencies of 28 ± 3% and 54 ± 4%, while COD removal efficiencies were relatively high at 87 ± 5% and 90 ± 5%, respectively. These results show that most of the COD was used for the denitrification process, but was insufficient for complete denitrification. It is at the COD:NO_3^- - N ratio of 3:1, where results showed most of both the nitrate and COD were treated. Nitrate and COD removal efficiencies were 99 ± 1% and 94 ± 3%, respectively. It can be concluded that a COD:NO_3^--N ratio as low as 3:1 can be used to treat both COD and nitrate with high efficiency. Previous research has shown that a COD:NO_3^--N ratio of around 5:1 is required for complete denitrification [20], and our current research reaffirms that a low COD:NO_3^- - N ratio is insufficient for complete denitrification, but proposes that complete denitrification is possible even at a COD:NO_3^- - N ratio of 3:1.

From the experimental analysis, COD removal is investigated at different COD:NO_3^--N ratios. In Fig. 4, the volume of organic carbon for removing nitrate in wastewater by denitrification is presented. After reaching steady states at each condition, nitrate removal increased as initial COD:NO_3^--N ratios increased. It can be seen that nitrate removal showed the lowest value at the ratio of 1:1, and it slightly increased as COD:NO_3^--N ratio was increased from 1:1 to 3:1. At COD:NO_3^--N ratios of 3:1, 5:1, and 10:1, the amount of nitrate removal was similar, suggesting that there was sufficient volume of organic carbon for complete denitrification as long as the COD:NO_3^--N ratio was higher than 3:1. The highest performance in term of combined nitrate and COD removal efficiencies was observed at the COD:NO_3^--N ratio of 3:1 (lowest COD and nitrate concentration in the effluent). While a previous research found that the appropriate stoichiometric COD:NO_3^- - N ratio for denitrification should be around 5:1 [20], our research differs from this previous research in that our experimental set-up utilized denitrifying bacteria in biofilm whereas the other research utilized suspended denitrifying bacteria. Another supporting research has found that denitrifying bacteria in biofilm could achieve better nitrate reduction activity than suspended denitrifying bacteria [21]. This is an advantage of biofilm processes for denitrification.



(b)

Fig. 3. The removal efficiency and variation of (a) nitrate and (b) COD in the influent and effluent at various COD:NO_3^--N ratios of 1:1, 2:1, 3:1, 5:1 and 10:1.

Moreover, it can be observed that excess COD can be reduced even after complete denitrification, as at an initial COD:NO_3^--N ratio of 10:1, more COD was ultimately removed than at initial COD:NO_3^--N ratios of 3:1 and 5:1 (As shown in Fig. 4). At the initial COD:NO_3^--N ratio of 10:1, the average amount of COD removed was 300 mg L^{-1}. It might be concluded that the denitrification and anaerobic conditions can occur simultaneously, known as simultaneous denitrification and anaerobic digestion. This phenomenon can be observed at high concentrations of carbon source. Unfortunately, at the initial COD:NO_3^--N ratio of 10:1, the ultimately remaining COD concentration was still high, translating to a low quality effluent. This low quality effluent will make it necessary to further treat the wastewater with other processes in order to increase the quality of the effluent. As such, it is ideal to use the correct and not an excess amount of COD for denitrification purposes, and the recommended COD:NO_3^--N ratio in a novel FBR for treating 100 mg L^{-1} of nitrate concentration in wastewater is 3:1.

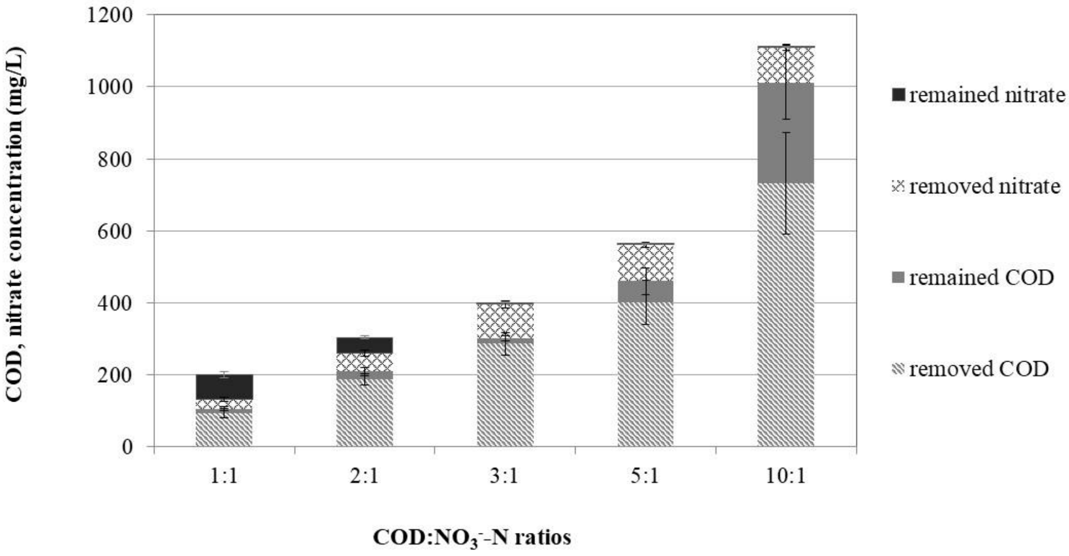


Fig. 4. Removed and remained substrate concentration at different COD to nitrate ratios. Data are shown as the mean ± SD.

To investigate the nitrate reduction and COD degradation profile along the reactor height, liquid samples from 10 sampling ports were collected. Data of each condition and reactor layer is shown in Fig. 5. Expectedly, nitrate and COD concentrations decreased continuously as it passed though the fluidized bed. At low COD:NO_3^- - N ratios of 1:1 and 2:1, the nitrate concentration and COD were gradually reduced at the bottom of the reactor to sampling port P2, as shown in Fig. 5(b). After sampling port P3, nitrate and COD concentration reached a steady state, and the subsequent effluent contained high nitrate and low COD concentrations. An average soluble COD of 18.7 ± 6.2 mg L^{-1} and average nitrate of 6.0 ± 2.5 mg L^{-1} were observed. At higher COD:NO_3^--N ratios of 5:1 and 10:1, most nitrate was removed at the bottom of the reactor with high residual COD present after port P2, particularly at the ratio of 10:1. The COD:NO_3^--N ratio of 3:1 was most appropriate for the treatment of both COD and nitrate, as the majority of both species were completely removed at the bottom of the reactor.

From all of the observed profiles, it could be concluded that COD and nitrate removal mostly occurred at the bottom of the reactor. This phenomenon depended on the COD:NO_3^--N ratio in wastewater.

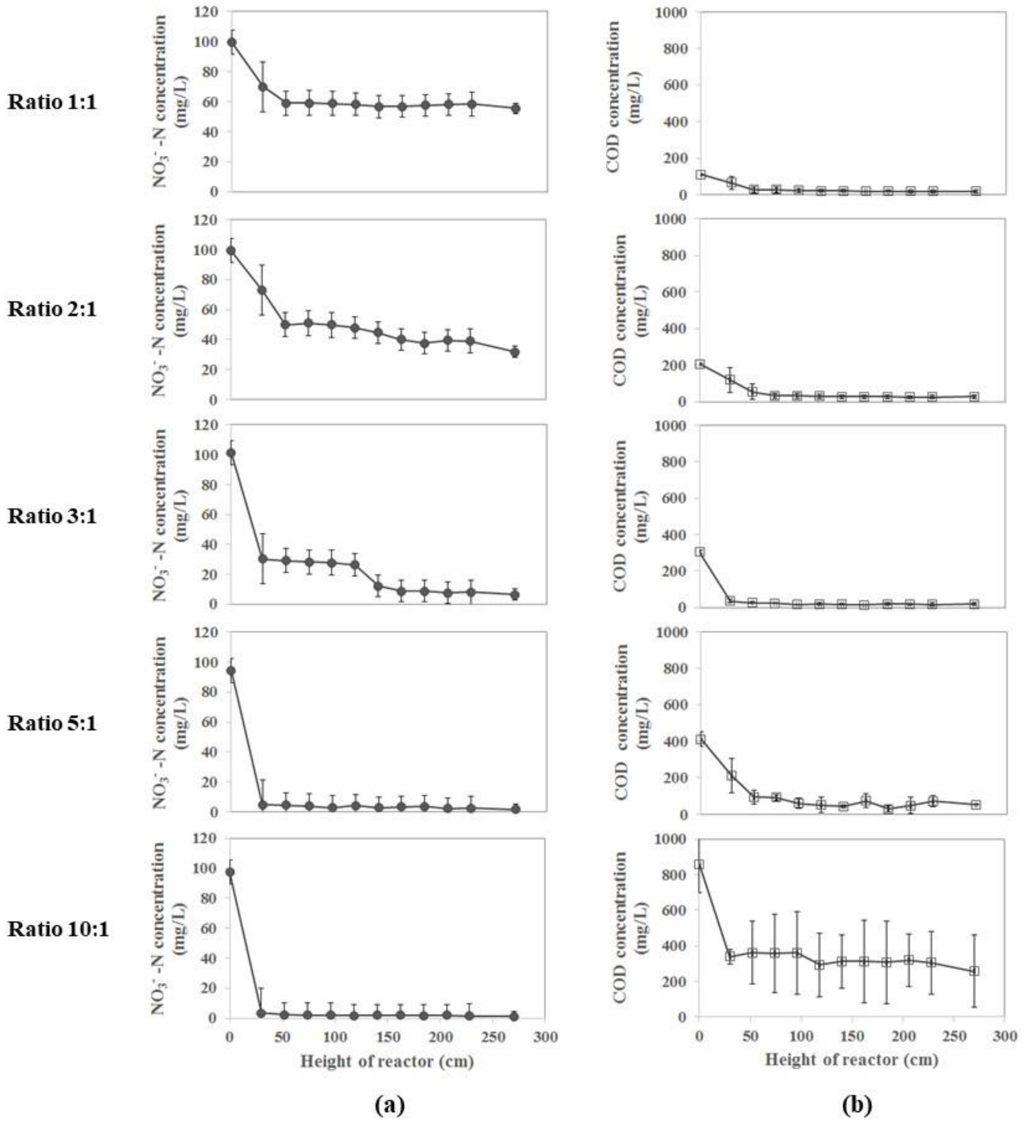


Fig. 5. Vertical profile of (a) nitrate and (b) COD removal along the height of the FBR, data are shown as the mean ± 1SD, derived from 3 independent trials.

3.3. The Performance of a Novel FBR for Low-strength Anaerobic Wastewater Treatment

A novel FBR was started to promote biofilm attachment onto fluidized media. Afterwards, various COD concentrations of wastewater were fed into the FBR to study the reactor's performance. The influent and effluent COD and operation times in each experiment are shown in Fig. 6, and the process parameters are shown in Table 3. It is observed that COD removal efficiency increased when COD influent decreased. The highest COD removal efficiency was found at an OLR of 5.6 g COD L^{-1} d^{-1}, or an equivalent COD concentration of 147 ± 19 mg L^{-1}.

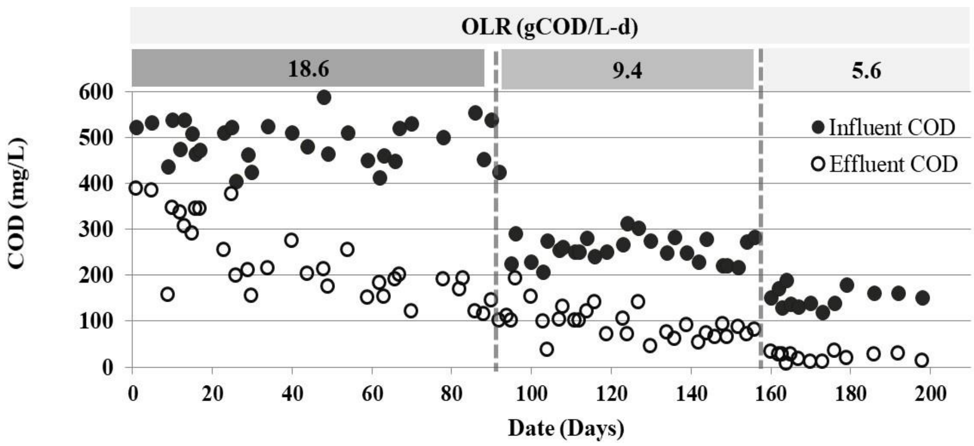


Fig. 6. Influent and effluent COD at different OLR operation.

Table 3. Steady state performance of the FBR treating low strength wastewater.

Parameters	OLR (g COD L^{-1} d^{-1})		
	5.6	9.4	18.6
Operation time (d)	38	64	94
Influent COD (mg L^{-1})	147 ± 19	252 ± 39	481 ± 48
Effluent COD (mg L^{-1})	21 ± 9	68 ± 18	191 ± 40
COD removal efficiency (%)	86 ± 6	71 ± 8	60 ± 7
Total suspended solid (mg L^{-1})	10 ± 4	28 ± 2	58 ± 28
CH_4 content in biogas (%)	15.11	28.60	45.99

After reaching steady state at initial OLRs of 5.6, 9.4, and 18.6 g COD L^{-1} d^{-1}, the results showed effluent COD concentrations of 21 ± 9, 68 ± 18, and 191 ± 40 mg L^{-1}, respectively. At an OLR of 5.6 g COD L^{-1} d^{-1}, COD removal efficiency was 86 ± 6%. However, at an OLR of 18.6 g COD L^{-1} d^{-1}, the COD removal efficiency was reduced to 60 ± 7%. It can be seen that an increase in influent COD concentration resulted in a decrease of COD removal efficiency. Our experimental values are in general lower than previous research, which reported that COD loadings of 10 - 20 g COD L^{-1} d^{-1} were appropriate for FBR in providing a COD removal efficiency greater than 90% [22]. One major difference between the current and previous research is that the HRT in the current research was drastically lower than previous research. As shown in various studies, low-strength anaerobic wastewater treatment should be operated at higher than 3 h of HRT, whereas the HRT of the current research was only 50 minutes [8, 23, 24].

Effluent suspended solid is a parameter commonly used to evaluate the performance of treatment systems. High quality effluent should contain low concentrations of suspended solids. In our study, total effluent suspended solids concentration was lowest at an OLR of 5.6 g COD L^{-1} d^{-1}, and it slightly increased as OLR increased. Still, at both OLRs of 5.6 and 9.4 g COD L^{-1} d^{-1}, suspended solids levels in the effluent were lower than the standard quality of effluent [25] allowed for municipal and industrial wastewater treatment, which are 30 and 50 mg L^{-1} respectively. This means that the effluent suspended solids levels achieved from this experiment can reach an acceptable quality for the effluent of municipal wastewater treatment plants.

Overall results demonstrated that the FBR achieved high performance for COD removal at OLRs of 5.6 and 9.4 g COD L^{-1} d^{-1}. At an OLR of 18.6 g COD L^{-1} d^{-1}, the results show low COD removal efficiency. As shown in Table 3, methane content in the biogas increased when the OLRs increased. Although the highest COD removal can be achieved at an OLR of 5.6 g COD L^{-1} d^{-1}, 15% of methane content was found in the biogas. At an OLR of 9.4 g COD L^{-1} d^{-1}, the methane content was 28.60%. At the highest OLR of 18.6 g COD L^{-1} d^{-1}, the result showed the highest methane content in the biogas at 45.99%. These results suggest that at low COD concentrations in the wastewater (at OLR of 5.6 and 9.4 g COD L^{-1} d^{-1}), oxygen in wastewater can be used by aerobic bacteria to reduce substrate in wastewater. With some portion of the carbon load consumed in aerobic conditions, lower corresponding methane content in the biogas can be observed.

4. Conclusions

The hydrodynamic behaviour study using the RTD experiment showed that the liquid flow pattern in a novel reactor was close to plug flow. This result can be used to modify and explain the novel FBR for further applications. With drastically low HRT, a novel FBR provided high performance for both denitrification and anaerobic treatment. In the denitrification process, a novel FBR exhibited high efficiency in both nitrate and COD removal, resulting in effluent with low substrate concentrations. Moreover, a novel FBR can achieve high performance in low strength wastewater treatment under anaerobic conditions. With its high substrate removal efficiency and no need for internal recirculation, the novel FBR is an interesting wastewater treatment alternative that also succeeds in energy conservation.

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