Investigation of furfural biodegradation in a continuous inflow cyclic biological reactor

Gholamreza Moussavi, Mostafa Leili and Kazem Nadafi

ABSTRACT

The performance of a continuous inflow cyclic biological reactor (CBR) containing moving media was investigated for the degradation of high concentrations of furfural. The effects of hydraulic retention time (HRT) and furfural initial concentrations (loading rate), as main operating parameters, on the bioreactor performance were studied. The results indicated that the CBR could remove over 98% of furfural and 71% of its chemical oxygen demand (COD) at inlet furfural concentrations up to 1,200 mg L\(^{-1}\) (2.38 g L\(^{-1}\) d\(^{-1}\)), a 6-h cycle time and HRT of 12.1 h. The removal efficiency decreased slightly from 98 to 94% when HRT decreased from 12.1 to 10.5 h. The average removal efficiency of furfural and COD during the 345-day operational period under steady-state conditions were 97.7% and 82.1%, respectively. The efficiency also increased approximately 17.2% after addition of synthetic polyurethane cubes as moving media at a filling ratio of 10%.

Key words | biodegradation, biological process, cyclic reactor, furfural, wastewater

INTRODUCTION

Furfural (C\(_5\)H\(_4\)O\(_2\)) is a toxic, colorless and soluble compound in water (maximum solubility is 83 g L\(^{-1}\) at room temperature) (Leili \textit{et al.} 2013), with a pungent almond-like odor. It can be used as an insecticide, fungicide, and germicide. Furthermore, furfural and its derivatives are used as a selective solvent in many industries such as phenol-furfural resins production plant, petroleum and oil refining, food, pulp and paper industries, rubber-manufacturing plants, chemical intermediates, weed killer, etc. (Hoydonckx \textit{et al.} 2000; Sahu \textit{et al.} 2008; Mebrek & Derriche 2010). Therefore, high concentration of furfural may be present in the effluent discharged from these industries. For instance, it was reported that furfural concentration in synthetic rubber plant wastewater can be about 1,700 mg L\(^{-1}\) (Sahu \textit{et al.} 2007; Leili \textit{et al.} 2013).

Humans can be exposed to furfural in several routes such as ingestion, percutaneous, respiration or via direct eye contact (Anbia & Mohammadi 2009). Exposures to furfural vapors via inhalation may produce headache, nausea, vomiting, central nervous system depression, weakness, and ataxia. Exposures with high concentrations or acute exposures may create pulmonary edema, unconsciousness and even death (Hoydonckx \textit{et al.} 2000; Wexler 2005). This compound can damage the liver and kidneys and if the exposures continue, it may cause tumors and mutations (Wexler 2005; Leili \textit{et al.} 2013). Given the potential hazards of exposures to furfural, the furfural-containing wastewater should be treated with appropriate technology to minimize the harmful effects. Several physical (Sahu \textit{et al.} 2008; Singh \textit{et al.} 2009), chemical (Borghei & Hosseini 2008; Chunjie \textit{et al.} 2009; Paramarzpour \textit{et al.} 2009; Leili \textit{et al.} 2013; Samarghandi \textit{et al.} 2014; Yang \textit{et al.} 2014; Samarghandi \textit{et al.} 2015), and biological (mainly anaerobic) techniques (Boopathy \textit{et al.} 1997; Taherzadeh \textit{et al.} 1999; Boopathy 2005; Zhang \textit{et al.} 2012) have been investigated to remove furfural from wastewater. Among these, biological processes are widely preferred because of their enormous and remarkable advantages including flexibility and reliability, convenient operation and maintenance, capability to eliminate a lot of contaminants, and economic benefits; moreover, it is environmental friendly technology which degrade contaminants to less toxic or harmful, and has the potential for full-scale applications, etc. (Moussavi & Heidarizad 2010).
Transformations or degradation of furfural by microbial metabolisms can occur under aerobic and anaerobic conditions (Modig et al. 2002; Yaghmaei et al. 2005; Almeida et al. 2009; Boopathy 2009). For instance, it can be reduced to furfuryl alcohol by a few microbial transformations such as Saccharomyces spp. Boopathy et al. (1997) showed that Methanococcus deltae can grow on H₂-CO₂ in the presence of various concentrations of furfural and transform it to furfuryl alcohol (Boopathy et al. 1997). Taherzadeh et al. (1999) investigated the effects of furfural on aerobic and anaerobic batch cultures of Saccharomyces cerevisiae and found that it decreases both the specific growth rate and ethanol production rate (Taherzadeh et al. 1999). Therefore, furfural has toxic and inhibitory effects on anaerobic biological systems, especially at high concentrations (Boopathy et al. 1997).

Based on our best literature review, there is a lack of work published on furfural removal from wastewaters using continuous flow cyclic biological reactors (CBR) seeded with the mixed culture and operated under aerobic conditions. In this study, the performance of CBR as a novel process was investigated for the degradation of high concentrations of furfural. This system is a promising modification and enhancement of the superior technology of the conventional sequencing batch reactors (SBR) to improve its performance (Moussavi et al. 2009). Advantages of this process are treating toxic and inhibitory compounds through mitigation of loading peak and shock in a single tank, small footprint, simple operation as well as allowing continuous treatment of wastewater in a single-basin bioreactor. In fact, this modification allows exploitation of the unique advantages of the conventional SBR and intermittent-cycle extended-aeration activated sludge (Moussavi & Heidarizad 2010). Aerating the reactor during the filling phase is a very important step from an operational point of view when the compound subjected to biotreatment is an inhibitor or recalcitrant; where the longer and continuous mode of feeding could improve removal efficiency (Irvine et al. 1989). Moreover, as was shown in my previous studies, reactor performance was improved by adding a few pieces of moving media (Moussavi et al. 2009), so the capability of the system in the presence of synthetic media was also examined. Accordingly, the influence of furfural loading rate (OLR) and hydraulic retention time (HRT), as the main operating parameters of the biological reactor were studied in biodegradation of furfural from aqueous solutions.

**MATERIALS AND METHODS**

### Preparing synthetic furfural wastewater with different concentrations

Feed furfural wastewater was prepared from dissolving known aliquots of furfural solution (analytical grade, purchased from Merck) in tap water in a 60 L container. Furfural is served as the sole carbon and energy substrate for the biomass. After regulating the concentration of furfural at the desired levels, the required nutrients (NH₄Cl, KH₂PO₄, and K₂HPO₄, as nitrogen and phosphorus sources, and trace elements) for microbial metabolism, were added to the prepared liquid to attain the ratio of C/N/P of 100/5/1 in the final feed. The pH of the feed wastewater was adjusted at the value of 7.3 ± 0.2, which is in the range of the optimum value for bacterial growth (Tchobanoglous et al. 2003).

**Apparatus and experimental set-up**

The CBR used in this study consisted of the following accessories: a cylindrical glass column as a bioreactor (internal diameter = 20 cm; total height = 56 cm and total volume ~11 L), an aeration system with a stone diffuser supplying air to maintain the dissolved oxygen at around 2.5 mg L⁻¹ in the mixed liquor over the aeration cycle time, a feeding system with a distributor installed at the bottom inside of the reactor, a decant system equipped with a time-control automatic operation system, tubing, valves and other accessories (Figure 1). A decant automatic time controlled valve was located at a height of 10 cm from bottom of the column giving a constant 3.1 L remaining volume (working volume or volume of mixed liquor remaining in the reactor at the end of the decant phase) in each operating cycle.

![Figure 1 | Schematic of the cyclic biological reactor.](https://iwaponline.com/wst/article-pdf/73/2/292/464507/wst073020292.pdf)
Biomass acclimation and reactor start-up

At the beginning of the experiment, preparation and acclimation of biomass was conducted as follows: 1 L of activated sludge from a laboratory-scale bioreactor that could efficiently treat a mixture of phenol and formaldehyde from wastewater in our previous study (Moussavi & Heidarizad 2010), was poured in an aerated stirred vessel. At the initial reaction condition, the suspension contained 6,000 ± 500 mg L⁻¹ of mixed liquor suspended solids (MLSS) which was kept constant at these ranges in all experimental phases of the study via daily wasting the mixed liquor. This biomass was previously acclimated and enriched to remove furfural while being first fed in batch mode (for about 10 days) with a daily exchange volume of 3.8 L (Q) of synthetic wastewater solution containing required nutrients and furfural loading rate of 0.59 g L⁻¹ d⁻¹. When the removal of furfural increased to 95%, the biomass was considered to be acclimated in furfural degradation. Following biomass acclimation, the reactor was operated as a CBR (detailed in Table 1) and fed with synthetic wastewater containing 600 mg L⁻¹ (1.19 g L⁻¹ d⁻¹) of furfural. This run of the experiment lasted 20 days. The OLR of furfural was progressively increased step by step (in four steps) up to 2.97 g L⁻¹ d⁻¹ over 345 d. In each step, 300 mg L⁻¹ (50% of initial concentration) was added to furfural initial and start-up concentration. The initial flow rate of the experiment was 3.8 L d⁻¹ (Q, correspond to HRT = 25.4 h). Similar to OLR, the feed flow rate was increased progressively in four steps to decrease HRT and the initial feed flow rate was increased up to 50% in each step. Additionally, the influence of cycle duration ranging from 6 to 24 h was assessed on the performance of the CBR. All experimental schedules of the study and phase timing are given in Table 1. The experimental set-up was operated at room temperature (23–25 °C) during the overall course of the investigation. Dissolved oxygen (DO) and pH of the mixed liquor were checked frequently using electrodes. The synthetic media (~10% of working volume) was added as suspended within the reactor had a characteristic of open-pore polyurethane foam with surface area of 600 m² m⁻³ (ENVICON, Germany) (Figure 1).

Analytical measurements

The concentration of furfural in the feed and decant streams was determined using a Unico-UV 2,100 UV/VIS spectrophotometer by measuring the absorbance at its maximum absorption wavelength (Sahu et al. 2007; Borghei & Hosseini 2008; Sahu et al. 2008). A standard solution of the furfural was scanned to determine the wavelength (λmax) corresponding to the maximum absorbance. From this scan, 277 nm was determined as λmax (Figure 2). The initial and final chemical oxygen demand (COD) were measured by the closed reflux method as described in method 5220 D (APHA 1998) (method 5220 D). The samples, which were taken from decanted supernatant, were filtered with a 0.45 µm filter prior to analysis.

RESULTS AND DISCUSSION

Biomass properties, acclimation and bioreactor start-up

The biomass, both in suspension and on the media, was characterized according to our previous study (Moussavi et al. 2009). The characteristics determined include the thickness of the biofilm formed on the media, the specific oxygen uptake rate (SOUR) of the biomass both on the moving media and in suspension, and the dominant bacteria species in the reactor. We found that the thickness of the biofilm was about 39 µm, the SOUR of the biofilm and the suspended biomass were about 3.1 mg mg⁻¹ volatile suspended solids (VSS) d⁻¹ and 0.32 mg mg⁻¹ VSS d⁻¹, respectively. This value was similar to the results of the Sá & Boaventura study (Sá & Boaventura 2001) for biological treatment of phenol. The results also revealed that the dominant species of the bacteria were heterotrophs as expected according to the literature (Sá & Boaventura 2001; Tchobanoglous et al. 2003).

Table 1 | Experimental phases and operational conditions

<table>
<thead>
<tr>
<th>Run</th>
<th>Day</th>
<th>Experiment</th>
<th>Cycle time (h)</th>
<th>HRT (h)</th>
<th>Loading rate (g L⁻¹ d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0–20</td>
<td>Biomass acclimation and reactor start-up</td>
<td>6</td>
<td>25.4</td>
<td>0.59–1.19 0.85–1.72</td>
</tr>
<tr>
<td>2</td>
<td>21–40</td>
<td>Effect of cycle time</td>
<td>6–24</td>
<td>25.4</td>
<td>1.19 1.72</td>
</tr>
<tr>
<td>3</td>
<td>41–213</td>
<td>Effect of HRT</td>
<td>6</td>
<td>10.5–25.4</td>
<td>1.19 1.72</td>
</tr>
<tr>
<td>4</td>
<td>214–345</td>
<td>Effect of volume loading rate</td>
<td>6</td>
<td>12.1</td>
<td>1.19–2.97 1.72–4.3</td>
</tr>
</tbody>
</table>
As mentioned previously, the bioreactor was started up as a SBR by injecting synthetic wastewater at each 6-h cycle period. The initial inlet furfural concentration was increased from 300 mg L\(^{-1}\) (OLR = 0.59 g L\(^{-1}\) d\(^{-1}\)) to 600 mg L\(^{-1}\) (OLR = 1.19 g L\(^{-1}\) d\(^{-1}\)) over 20 d. As shown in Figure 3, after 10 days of start-up with an initial concentration of 300 mg L\(^{-1}\), the removal efficiency increased from 48.33 to 96%. On the 11th day of the start-up, two major changes occurred: the inlet concentration of furfural increased to 600 mg L\(^{-1}\), and the reactor operation mode was changed to continuous instead of being batch; this caused a deterioration of the effluent quality in terms of furfural concentration and turbidity. From the appearance judgments and turbidity measurement of effluent, this could be due to washout of the biomass from the reactor caused by flow or concentration shock. As can be seen in Figure 3, the removal of furfural decreased to below 82% after the increase of inlet concentrations. In this stage, a few pieces of the media were added to the reactor as suspended and its contribution in the reactor and its contribution in the improvement of reactor performance was assessed. These synthetic media picked up from the reserve aeration reactor that operated beside the main reactor feed with constant daily concentration of 500 mg L\(^{-1}\) of furfural from the beginning of the experiments. After 20 days, furfural removal increased up to 99.2% at the initial concentration of 600 mg L\(^{-1}\), showing the success of the start-up. Thus, the addition of the synthetic media to the bioreactor improved reactor performance via keeping the biomass more in contact with the pollutant and preventing its washout (Moussavi & Heidarizad 2010), thereby increasing the furfural removal efficiency.

**Figure 2** | Spectra of furfural solution absorption at the wavelength between 200 and 600 nm.

**Figure 3** | Furfural and COD removal efficiency during the bioreactor start-up.

**Contribution of the moving media to the reactor’s performance**

The contribution of the applied media to the removal of furfural was calculated through the difference of the furfural
removal efficiencies before and after the addition of media to the reactor (Moussavi & Mohseni 2008) and was found to be more than 17% in the study. This improvement might be due to biofilm activity, moving the synthetic media throughout the reactor which, in turn, increases the mass transfer rate of furfural and oxygen transport efficiency from the bulk phases to the biomass and thin thickness of the biofilm (Moussavi et al. 2009). Thus, the biofilm is not limited to furfural removal as it also improves the rate of compound elimination.

Effect of aeration cycle time

In cyclically operated systems, the length of the cycle time affects both the size and thus the cost of treatment, and substrate degradation kinetics. Hence, the cycle time was considered one of the main operational parameters, affecting process performance (Dionisi et al. 2007; Liu & Tay 2007; Moussavi & Heidarizad 2010). In order to assay aeration cycle time’s effects on the degradation of furfural and corresponding COD removal, three runs were performed at cycle lengths of 6 h, 12 h and 24 h (corresponding to four, two and one cycle(s) per day, respectively. This was done by adjusting the length of the aeration stage to the appropriate value under steady-state conditions (Table 1) to find the lowest value at which the treatment objectives could be achieved. During this phase of the study, the settling and decant time was kept constant at 1.5 h and 0.5 h, respectively, and at each cycle time, the bioreactor was monitored to attain a steady-state condition and operated for 10 d at such conditions. Figure 4 depicts the average pseudo steady-state removal efficiencies of furfural and COD, while Figure 5 demonstrates the variation of furfural and corresponding COD removal efficiencies in the CBR at various aeration times. As seen in Figure 5, the increase of aeration cycle time had little impact on the efficiency in all experimented aeration cycle times. The mean furfural removal efficiency at all conditions was more than 93%. Nevertheless, it had significant effect on COD removal efficiency and by increasing the aeration cycle time, the removal efficiency of COD also increased. For instance, the average COD removal efficiency of 6-h cycle time was about 46.6%, while by increasing the cycle time to 24 h, the COD removal efficiencies increased up to 91.1%. The increase of MLSS from 9,000 mg L\(^{-1}\) in a 6-h cycle time to about 11,500 mg L\(^{-1}\) in 24-h cycle time due to more acclimation of biomass and period of aeration (a longer period of the aeration step enhances the microbial growth and multiplication in the reactor) (Liu & Tay 2007; Tsang et al. 2007), the presence of moving media throughout the reactor, or the independence of the biomass retention time from inflow rate, and the mode of feeding (Moussavi & Heidarizad 2011) are the main reasons for this improvement. On the one hand, the increase of cycle time resulted in high removal efficiencies but, on the other hand, the shorter the cycle duration, the lower the treatment cost and more reasonable the bioreactor cost would be (Tsang et al. 2007). However, the lower limit of the cycle time, which is related to hydraulic retention time that had a noticeable impact on the choice of cycle time, is dictated by the time required for the oxidation reaction of the entering substrates and from the perspective of kinetic behavior of bacteria involved in furfural degradation (Liu & Tay 2007; Moussavi & Heidarizad 2010). In addition, low loading rate combination with long cycle time resulted in low sludge production (Liu & Tay 2007). Therefore, the balance between advantages by shortening cycle time and disadvantages should be considered for the full-scale applications. Tsang et al. (Tsang et al. 2007) also showed that when aeration time was longer than 6 h, aged sludge was formed, the
growth of the sludge was brought to an end and excessive growth of protozoa and rotifers could occur. It must be noted that the minimum HRT that we had decided to assay in the next section of the study was 10.5 h which it could be possible if the 6-h cycle time was chosen. Hence, the 6-h cycle time (aeration: 4 h, settling: 1.5 h, and decant: 30 min) was selected based on effluent quality and economic considerations as optimum cycle duration for further investigation.

**Effect of hydraulic retention time (HRT)**

In this phase of the experiment, the effect of various wastewater HRTs of 10.5 h (4Q) to 25.4 h (Q) was studied on the performance of the CBR on furfural degradation and corresponding COD removal. The detailed operating conditions of this phase of study are shown in Table 1. At each step, the bioreactor was operated until a pseudo steady-state condition was attained. As shown in Figure 6, furfural degradation and COD removal efficiency in all conditions were very high and did not come under 98% and 90%, respectively; with the exception for HRT of 10.5 h that furfural degradation and COD removal efficiencies dropped to 94% and 58.4%, respectively. For furfural, the selected HRTs did not significantly affect the removal percentages, inferring that the HRT was always enough to achieve furfural biodegradation. When switching the CBR operation from one HRT to another condition, the transient decrease in the reactor performance was observed but this condition immediately was improved during about the next 2–3 days. Further details in each HRT change during the first four cycles are shown in Table 2. However, after passing five cycles for each experimental run, removal efficiencies recovered to an average of more than 98% and 90% for furfural and COD, respectively. It is also clear from Table 3 that the average removal of both furfural and COD in all various HRTs were high. Although as seen in Table 3, for run A5 of the HRT experiment, there was a sharp decrease in reactor performance on COD removal efficiency but furfural removal efficiency was still high (94%). Therefore, it was implied that the sensitivity of the CBR to HRT at lower values was higher than larger ones. However, this low HRT can be of great value compared to relatively high retention time required in anaerobic systems designed to remove furfural from wastewater (Wirtz & Dague 1995; Boopathy et al. 1997).

**Effect of furfural loading rate**

The effect of furfural loading rate in the range of 1.19–2.97 g L\(^{-1}\)d\(^{-1}\), corresponding to the furfural concentration of 600–1,500 mg L\(^{-1}\) on the reactor performance was studied during 131 days with a constant cycle time of 6 h/cycle. The reactor was operated at each concentration until steady-state performance in furfural removal was achieved. Figure 7 shows the profiles of furfural and COD removal variations at different inlet furfural concentrations and mean furfural and COD removal efficiency at each furfural loading rate are shown in Figure 8. At loading rate of 1.19 g L\(^{-1}\)d\(^{-1}\) (C) to 2.38 g L\(^{-1}\)d\(^{-1}\) (2 C), furfural removal efficiency was high (>99%) but when loading rate was
increased to 2.5 C (2.97 g L\(^{-1}\) d\(^{-1}\)), the removal efficiency dropped to about 76.9%. A same pattern was observed for COD removal with the increases of loading rate, but COD removal efficiency reduced at a higher rate than that of furfural. For instance, COD removal efficiency was >76% for loading rates up to 2 C, but when loading rate was increased to 2.97 g L\(^{-1}\) d\(^{-1}\) (2.5 C), the removal efficiency declined to about 53.6%. As shown in Figure 7, the removal efficiency further reduced and the time to attain steady state further increased at higher inlet COD concentrations. It can also be seen from Figure 7 that after about 10 days of loading rate changes, CBR performance in high furfural removal efficiency again recovered but a downward trend on COD removal efficiency continued. The upper limit of loading rate (2.97 g L\(^{-1}\) d\(^{-1}\), corresponds to 1,500 mg L\(^{-1}\) of furfural) that effectively treated with relatively high removal efficiency in this study was higher than that obtained by other researchers through adsorptive (Sahu et al. 2013; Singh et al. 2013), photooxidation (Borghei & Hosseini 2008; Chun-li et al. 2009; Faramarzpour et al. 2009) and biological (Zeitsch 2000) methods. Furthermore, the removal efficiency for furfural-loading rate up to 2.38 g L\(^{-1}\) d\(^{-1}\) (1,200 mg L\(^{-1}\) of furfural) that effectively treated with relatively high removal efficiency in this study was higher than that obtained by other researchers through adsorptive (Sahu et al. 2008; Singh et al. 2009), photooxidation (Borghei & Hosseini 2008; Chun-li et al. 2009; Faramarzpour et al. 2009) and biological (Zeitsch 2000) methods. Furthermore, the removal efficiency for furfural-loading rate up to 2.38 g L\(^{-1}\) d\(^{-1}\) (1,200 mg L\(^{-1}\) of furfural) obtained in this study was also excellent and greater than 99%. The low COD removal at high furfural loading rate suggests the limitation of the furfural uptake and degradation by the bacterial culture. From the results of furfural removal, the steady-state operation for all studied loading rates were in the range of 1–2 days, with the exception of 2.5 C for which removal efficiency decreased and it took about 4–5 days to reach the steady state condition. It was also found that the time required to reach the steady-state for COD removal became longer than that of furfural with increasing loading rate.

**Biodegradation of furfural and COD**

Figure 9 shows the time-dependent inlet furfural and COD concentrations and the efficiency of the reactor. During

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**Table 3** | Average furfural and COD removal efficiencies during total 10 months of reactor operation

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Run</th>
<th>Day</th>
<th>HRT (h)</th>
<th>Loading rate (g L(^{-1}) d(^{-1}))</th>
<th>Removal efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRT effect</td>
<td>A1</td>
<td>41–119</td>
<td>25.4</td>
<td>1.19</td>
<td>99.75  92.38</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>120–147</td>
<td>18.7</td>
<td>1.19</td>
<td>99.75  93.53</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>148–179</td>
<td>15.4</td>
<td>1.19</td>
<td>99.78  93.61</td>
</tr>
<tr>
<td></td>
<td>A4</td>
<td>180–200</td>
<td>12.1</td>
<td>1.19</td>
<td>98.74  90.60</td>
</tr>
<tr>
<td></td>
<td>A5</td>
<td>201–213</td>
<td>10.5</td>
<td>1.19</td>
<td>93.99  58.39</td>
</tr>
<tr>
<td>Furfural loading rates effect</td>
<td>B1</td>
<td>214–236</td>
<td>12.1</td>
<td>1.19</td>
<td>99.01  65.60</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>237–257</td>
<td>12.1</td>
<td>1.78</td>
<td>99.45  74.64</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>258–323</td>
<td>12.1</td>
<td>2.38</td>
<td>99.13  76.00</td>
</tr>
<tr>
<td></td>
<td>B4</td>
<td>324–345</td>
<td>12.1</td>
<td>2.97</td>
<td>76.88  53.58</td>
</tr>
</tbody>
</table>

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Figure 7 | Profiles of furfural and COD removal efficiencies for various inlet concentrations.

Figure 8 | Average furfural and COD removal efficiency at different furfural loading rates.

Figure 9 shows the time-dependent inlet furfural and COD concentrations and the efficiency of the reactor. During
the long-term operation of above 10 months, influent furfural concentration and feed flow gradually increased from 600 (OLR of 1.19 g L\(^{-1}\) d\(^{-1}\)) to 1,500 mg L\(^{-1}\) (OLR of 2.97 g L\(^{-1}\) d\(^{-1}\)) and 3.8 L d\(^{-1}\) (HRT of 25.4 h) to 15.2 L d\(^{-1}\) (10.5 h), respectively. The effects of HRT changes on the reactor performance were studied over the first 180 days of the experiment (Run A: A1–A5) and also the furfural loading rate effects on removal efficiency were studied during about 120 days of remaining reactor operation (Run B: B1–B4). It was observed that the final furfural concentration in the effluent was in the range of 0–400 mg L\(^{-1}\) and the average removal efficiencies of furfural and COD during the operational period were about 97.72% and 82%, respectively. The minimum furfural removal efficiency of around 77% was obtained at inlet concentrations of 1,500 mg L\(^{-1}\) and HRT of 12.1 h increased up to ∼100% at HRT of 25.4 h. Similarly, the minimum and maximum COD removal efficiencies were obtained at the same conditions obtained for furfural. The average removal efficiencies of furfural and COD during the total operational period were approximately 97.72% and 82%, respectively. In conclusion, the capability of this developed system to remove high concentrations of furfural in a relatively short HRT increased the value of the study and made it a technically and economically feasible and promising technology for industrial applications.

**CONCLUSION**

A laboratory-scale cyclic biological reactor (CBR) was continuously operated with synthetic wastewater for over 10 months without any operating problems and high removal efficiencies of both furfural and COD were obtained. The removal efficiency of furfural was above 98% except at 10.5 h of total HRT and furfural loading rate of 2.97 g L\(^{-1}\) d\(^{-1}\) for which it decreased to about 94% and 77%, respectively. High COD removal efficiency, above 90% at furfural loading rate of 1.19 g L\(^{-1}\) d\(^{-1}\) (600 mg L\(^{-1}\)) except for 10.5 h HRT, was also achieved. The minimum furfural removal efficiency was obtained at inlet OLR of 2.97 g L\(^{-1}\) d\(^{-1}\) (1,500 mg L\(^{-1}\)) and HRT of 12.1 h increased up to ∼100% at HRT of 25.4 h. Similarly, the minimum and maximum COD removal efficiencies were obtained at the same conditions obtained for furfural. The average removal efficiencies of furfural and COD during the total operational period were approximately 97.72% and 82%, respectively. In conclusion, the capability of this developed system to remove high concentrations of furfural in a relatively short HRT increased the value of the study and made it a technically and economically feasible and promising technology for industrial applications.

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