A novel post-treatment system, jet loop reactor (JLR), was proposed for anaerobic bioreactor effluent polishing purposes. The performance of the JLR, with respect to residual organics, total Kjeldahl nitrogen (TKN) and ammonia-nitrogen removal at different hydraulic retention times (HRTs), was the main focus of this study. The JLR, on average, was capable of removing approximately 99% of ammonia-nitrogen and 95% of TKN at HRTs of 8 and 5 h, respectively. The integrated system had an average removal of more than 85% of total BOD and COD and more than 95% of filtered BOD and COD. However, the JLR did not have a consistent performance due to dynamic MLSS concentration (and SRT). Overall the results indicate that the JLR can be considered as a feasible alternative for post-treatment of anaerobic bioreactor effluent.

Key words: anaerobic bioreactor effluent, jet loop reactor, hydraulic retention times, nitrification, post-treatment, upflow anaerobic sludge blanket reactor

Introduction

Anaerobic biotechnology has traditionally been used for excess sludge digestion of municipal sludge and for the treatment of high-strength industrial wastewaters. This is one of the oldest processes applied for the stabilization of biosolids and still remains as the dominant process for sludge stabilization. In recent years, considerable attention has been paid to anaerobic biotechnologies for treatment of low-strength wastewater. Among them, the upflow anaerobic sludge blanket (UASB) bioreactor is proven to be a reliable technology (van Haandel and Lettinga 1994); however, treatment by the UASB reactor itself is not sufficient to meet typical effluent discharge standards (e.g., BOD = 30 mg/L and SS = 30 mg/L).

Several researchers have suggested the need to integrate a simple aerobic post-treatment unit for the anaerobic bioreactor effluent polishing purposes (Colliviognarelli et al. 1990; Tilche et al. 1996; Chernicharo and Machado 1998). Recent investigations have demonstrated that it is feasible to use an aerobic post-treatment system in treating anaerobically pretreated effluent (Agrawal et al. 1997; Tawfik et al. 2001; Tandukar et al. 2004). Implementation of combined anaerobic-aerobic processes for high-strength wastewaters has been demonstrated to be feasible (Driessen et al. 2004; von Sperling et al. 2001); however, utilization of this technology for treatment of low-strength wastewaters is still under development, and limited information is available on the technical feasibility of an integrated anaerobic-aerobic bioreactor system. In addition, none of the integrated systems developed thus far assures satisfactory effluent quality, constructional/operational simplicity, energy and cost effectiveness. A review by Jordao and Sobrinho (2004) on investigation and experience with post-treatment for UASB in Brazil has shown that a final effluent quality of 30 mg/L of BOD and TSS is consistently achievable; however, effluent ammonia-nitrogen concentration is typically greater than 20 mg/L.

Therefore, this study aimed to develop a novel integrated anaerobic-aerobic biological system, consisting of a UASB reactor and a jet loop reactor (JLR). The UASB reactor was used as a pretreatment unit because of its inherent superior characteristics such as low sludge production, operational simplicity and low operational costs. The JLR is of particular interest as the post-treatment unit because of its compactness, superior oxygen transfer, ease of maintenance and superior mixing capabilities (Bloor et al. 1995). The JLR utilizes high volume, low head centrifugal pump to recycle the biomass and wastewater through a liquid header and discharges them at high velocity through a venturi/nozzle. A venturi, designed based on Bernoulli’s principle, essentially consists of a convergent and a divergent cone with a constricted zone in the middle. Velocity of the compressed liquid increases as it passes through the constricted zone resulting in energy dissipation. Pressure drops as energy dissipates creating a vacuum within the constricted zone enabling atmospheric air to be drawn in. As the compressed jet stream is diffused towards the outlet, fine dispersed air bubbles are generated promoting better oxygen transfer, higher degree of turbulence and mixing,
thus facilitating optimal mass transfer and good biological conversion (Mazzei 2004).

The specific objectives of the study were to: (a) demonstrate the technical feasibility and effectiveness of using the JLR as a post-treatment system for residual organics and ammonia-nitrogen removal treating the effluent from the UASB reactor at different HRTs; (b) determine the nitrification efficiency of the JLR at different OLRs and F/M ratios; (c) evaluate the overall performance of the integrated UASB-JLR system for simultaneous removal of residual organics and ammonia-nitrogen at different HRTs; and (d) compare the performance of the integrated system with other integrated systems.

Materials and Methods

Experimental Setup

The integrated lab-scale system consisted of a UASB reactor (3.1 L) followed by a JLR (2.6 L) and a conventional clarifier (1.4 L), as shown in Fig. 1. The reactors were connected in series. The effluent from the UASB reactor was directly discharged into the JLR. The JLR was made of a cylindrical plexiglass column with a height of 77 cm and an internal diameter of 8.5 cm. A chlorinated polyvinyl chloride (CPVC) draft tube, 1.3 cm in diameter and 51 cm in height, was installed in the middle of the column. The venturi (Mazzei model 384, Mazzei Injector Corporation, Ca., U.S.A.) was installed on the top of the reactor and the mixed liquor suspended solids (MLSS) were pumped through it at a pressure of 2 psi, which drew in atmospheric air for oxygen transfer and mixing. A recycle line was introduced into the JLR for the continuous recirculation of the sludge, with the sludge recycle ratio of 0.4 of the influent flow to JLR from the clarifier (surface area of 0.52 m² and a depth of 40 cm) back into the JLR. A valve was installed within the sludge recycle line for sampling.

Seed Sludge

The UASB reactor was seeded with 1.5 L of granular sludge obtained from a full-scale expanded granular sludge bed (EGSB) anaerobic reactor used for treating wastewater from a potato processing plant (McCain Food Ltd., Grand Falls, Canada). The JLR was seeded with sludge collected from the return sludge line of the City of Fredericton activated sludge municipal wastewater treatment plant. The sludge volume index (SVI) of the JLR seed sludge was 78 mL/g. The seed sludge was diluted to an MLSS concentration of 1226 mg/L with a volatile fraction content of 73%.

Operating Conditions

The study was conducted at an average room temperature of 23°C for a period of 7 months. Influent to the
JLR was the effluent of the UASB reactor, fed with low-strength sucrose-based synthetic wastewater, as shown in Table 1. The alkalinity required (approximately 800 mg/L as CaCO3) for buffering was provided by the addition of sodium bicarbonate (NaHCO3) and the system pH was maintained within the range of 6.8 to 7.2. The HRT of the JLR was determined based on corresponding flow of influent to the UASB reactor, as the two reactors were connected in series. The first phase of the study was concentrated on the start-up of the UASB reactor by increasing the OLR of the UASB reactor from 0.7 kg COD/m3⋅d to 0.9 kg COD/m3⋅d (which corresponds to a decrease in HRT from 24 to 16 h). The JLR was started up before the UASB reactor reached its steady-state at an HRT of 16 h (which corresponds to HRT = 13 h in the JLR). Subsequent phases focused on the strategy of decreasing the HRTs of both reactors simultaneously, as shown in Table 2. Each phase of the study only lasted for approximately a month due to time limitations.

Analytical Methods

Total and filtered COD concentrations were determined using a DR/870 Hach colorimeter with the colorimetric method. Total BOD, filtered BOD, SVI, TSS, VSS, MLSS and MLVSS parameters were determined according to Standard Methods (APHA, AWWA, WEF 1995). TKN, ammonia-nitrogen (NH4-N), nitrate-nitrogen (NO3-N), and nitrite-nitrogen (NO2-N) concentrations were determined using Hach procedures (Hach 1999). Routinely, pH values were monitored using an Acument Basic AB 15 pH meter. Dissolved oxygen (DO) concentration was measured with a DO meter (YSI Model 58). Oxidation-reduction potential (ORP) was measured with Cole Palmer general purpose ORP probe (AgCl reference cell). DO, pH and ORP were measured by grab sampling.

Nitrogen conversion efficiency was obtained as follows:

\[
\text{Influent JLR} - \text{TKN} = \text{effluent JLR} - \text{nitrate-nitrogen} + \text{effluent JLR} - \text{nitrite-nitrogen} + \text{effluent JLR} \text{ammonia-nitrogen} + \text{TKN}
\]

Nitrogen utilized for biomass synthesis was estimated based on the difference between the influent and effluent total nitrogen concentration (assuming negligible testing errors). All calculations were conducted based on data collected during the stable period (pseudo steady-state conditions). The stable period is defined as a two-week period when performance parameters such as COD, BOD and nitrogen concentrations in the effluent of JLR were found almost constant.

Results and Discussion

Performance of the JLR

Time series of COD (total and filtered) and BOD (total and filtered) concentrations in the influent and effluent of the JLR are presented in Fig. 2 and 4, respectively. Figure 3 shows the time series of COD (total and filtered) removal for the JLR. As illustrated in Fig. 3, there was no COD removal during the first week of start-up of the JLR (but a negative trend). This could be due to the background COD available in the seed sludge and the initial washout from the JLR (Fig. 6). Total COD removal by the JLR was 40.9 ± 14.5, 61.0 ± 11.0, 36.0 ± 13.2 and 18.4 ± 10.2% and filtered COD removal was 84.3 ± 11.8, 79.1 ± 11.3, 85.8 ± 6.8 and 78.7 ± 3.3% at HRTs of 8, 5, 3 and 2.5 h, respectively (Fig. 3). Total BOD removal was 50.0 ± 9.9, 72.0 ± 3.7, 58.6 ± 0.3, and 58.8 ± 1.2 and filtered BOD removal was 88.0 ± 2.1, 94.0 ± 1.3, 93.7 ± 1.5 and 92.4 ± 0.5% at HRTs of 8, 5, 3 and 2.5 h, respectively (Fig. 5). The data indicated that decreasing the HRTs of the UASB reactor from 10 to 3 h (and from 8 to 2.5 h in the JLR) resulted in an overall reduction of COD and BOD removal efficiency.

The effluent TSS concentrations of the JLR were 36.9 ± 18.7, 22.7 ± 6.0, 87.7 ± 81.4 and 72.2 ± 55 mg/L for HRTs of 8, 5, 3 and 2.5 h, respectively (Fig. 6). Oxidation-reduction potential (ORP) was measured with Cole Palmer general purpose ORP probe (AgCl reference cell). DO, pH and ORP were measured by grab sampling.

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\]

Nitrogen utilized for biomass synthesis was estimated based on the difference between the influent and effluent total nitrogen concentration (assuming negligible testing errors). All calculations were conducted based on data collected during the stable period (pseudo steady-state conditions). The stable period is defined as a two-week period when performance parameters such as COD, BOD and nitrogen concentrations in the effluent of JLR were found almost constant.

Results and Discussion

Performance of the JLR

Time series of COD (total and filtered) and BOD (total and filtered) concentrations in the influent and effluent of the JLR are presented in Fig. 2 and 4, respectively. Figure 3 shows the time series of COD (total and filtered) removal for the JLR. As illustrated in Fig. 3, there was no COD removal during the first week of start-up of the JLR (but a negative trend). This could be due to the background COD available in the seed sludge and the initial washout from the JLR (Fig. 6). Total COD removal by the JLR was 40.9 ± 14.5, 61.0 ± 11.0, 36.0 ± 13.2 and 18.4 ± 10.2% and filtered COD removal was 84.3 ± 11.8, 79.1 ± 11.3, 85.8 ± 6.8 and 78.7 ± 3.3% at HRTs of 8, 5, 3 and 2.5 h, respectively (Fig. 3). Total BOD removal was 50.0 ± 9.9, 72.0 ± 3.7, 58.6 ± 0.3, and 58.8 ± 1.2 and filtered BOD removal was 88.0 ± 2.1, 94.0 ± 1.3, 93.7 ± 1.5 and 92.4 ± 0.5% at HRTs of 8, 5, 3 and 2.5 h, respectively (Fig. 5). The data indicated that decreasing the HRTs of the UASB reactor from 10 to 3 h (and from 8 to 2.5 h in the JLR) resulted in an overall reduction of COD and BOD removal efficiency.

The effluent TSS concentrations of the JLR were 36.9 ± 18.7, 22.7 ± 6.0, 87.7 ± 81.4 and 72.2 ± 55 mg/L for HRTs of 8, 5, 3 and 2.5 h, respectively, as shown in Fig. 6. Effluent TSS concentration was high at lower HRTs of 3 and 2.5 h due to the poor sludge settling characteristics (SVI = 277.8 ± 60.0 mL/g) (Fig. 7). Bloor et al. (1995) reported poor sludge settleability as one of the most serious problems with the JLR in the treatment of brewery wastewater for COD and BOD removals. In this study, the JLR also exhibited poor sludge settleability concern although the JLR was used as a nitrifying reactor. It was unanticipated for the flocs’ deflocculation to arise in the later stages of the study. This could be attrib-
TABLE 2. Operating conditions of the JLR

<table>
<thead>
<tr>
<th>HRT of the UASB (h)</th>
<th>HRT of the JLR (h)</th>
<th>F/M (kg COD/kg MLVSS ⋅ d)</th>
<th>OLR (kg COD/m³ ⋅ d)</th>
<th>ALR (kg NH₄-N/m³ ⋅ d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<td>13</td>
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<tr>
<td>4</td>
<td>3</td>
<td>3.16</td>
<td>0.88</td>
<td>0.46</td>
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</table>

Fig. 2. Time series of influent and effluent COD of the JLR.

Fig. 3. Time series of COD removal of the JLR.

Fig. 4. Time series of influent and effluent BOD of the JLR.

Fig. 5. Time series of BOD removal of the JLR.

Fig. 6. Time series of influent and effluent TSS of the JLR.

Fig. 7. Time series of SVI of the JLR.
uted to high shear force exerted by the venturi, higher F/M ratio, high organic loading rates (OLRs) and the high turbulence in the JLR. Further studies are necessary to investigate the effect of shear forces exerted by the venturi, the effect of F/M ratio, the effect of OLRs and the effect of turbulence on sludge settleability in the system. Reflocculation may occur under the right operating conditions of the JLR (i.e., organic loading rate, recycle flow rate, size of venturi, etc.). Jenkins (1992) reported that characteristics of the effluent deteriorated above a certain level of turbulence due to breakage of filamentous organisms and the deflocculation of biological flocs.

The MLSS concentration of the JLR was hard to maintain throughout the study (Fig. 8). Therefore, both the UASB and JLR reactors were connected in series to build up and sustain the SS inventories in the JLR. In addition, sludge recycle ratio from the clarifier back into the JLR was reduced from 0.8 to 0.4 times the influent flow to JLR on day 70 and maintained at that level till the end of the study. Peaks shown in Fig. 7 indicate biomass washout from the UASB reactor leading to an increase in MLSS concentration of the JLR. Yang (1994) recommended placing an intermediate clarifier after the UASB reactor to trap the anaerobic sludge washed out from the reactor and to reduce the amount of mixing with the aerobic sludge since the two types of sludge are not considered compatible. However, no significant impact on the performance of the JLR was found in the present study even though the JLR directly received effluent discharged from the UASB reactor.

It was found that the integrated system achieved more than 93% of total BOD removal at all HRTs, leaving a final effluent total BOD concentration of less than 21 mg/L (Fig. 4). There was no difference in filtered BOD and COD removal at any of the HRTs, leaving a final effluent filtered BOD and COD concentration of less than 4 and 20 mg/L, respectively (Fig. 2 and 4).

The COD removal efficiency obtained in this study was higher than those reported by Chernicharo and Nascimento (2000). They reported COD removal of 74 to 88% in an UASB-trickling filter (TF) system treating raw domestic wastewater at a total HRT of 7 h. Souza and Foresti (1996) reported COD removal of 95% using UASB-SBR system treating synthetic domestic wastewater, with a final effluent COD of 150 mg/L at a combined HRT of 8 h. Moreover, total COD removal obtained in the present study compared well with results from other post-treatment systems such as wastewater stabilization pond (WSP) and integrated duckweed and stabilization pond system (Dixo et al. 1995; van der Steen et al. 1999). The JLR in general provided higher COD removal efficiency at lower HRTs. Furthermore, the COD removal efficiency obtained in this study is similar to those obtained: (i) in UASB-hanging sponge cube process (HSCP) system by Agrawal et al. (1997) at a total HRT of 8 h; (ii) in UASB-biofilter (BF) system by Gonçalves et al. (1998) at a total HRT of 8 h; (iii) in UASB-activated sludge process (ASP) system by Tawfik et al. (2001, 2002) at a total HRT of more than 10 h. In the last three studies (Gonçalves et al. 1998; Tawfik et al. 2001; Tawfik et al. 2001, 2002) HRT values were much higher than those considered in this study.

### Nitrogen Removal

Figures 9 and 11 show the time series of effluent nitrogen and TKN distribution for the JLR. The start-up period of the JLR as nitrifying reactor was less than three weeks, which is shorter than other post-treatment systems (ASP, TF, RBC, BF, WSP, etc.), and compare satisfactorily with the attached-growth type of system such as TF, RBC, BF and “fourth generation” downflow hanging sponge reactors (Tandukar et al. 2004). The “fourth generation” downflow hanging sponge reactors is better than TF, RBC and BF because it requires neither external aeration input nor withdrawal of excess sludge and has higher specific surface area.
The average final effluent NH$_4$-N and TKN concentrations from the UASB reactor was 51.2 ± 3.8 and 61.7 ± 1.4 mg/L, respectively (Fig. 9 and 11). The NH$_4$-N and TKN removal in the UASB reactor were not significant, as the reductive environment within the UASB reactor did not provide any further reduction of these reduced compounds. TKN analysis indicated that 6% of the added organic nitrogen was assimilated for biomass production of the anaerobic sludge, regardless of the HRTs of the UASB reactor (Fig. 10).

The ammonia loading rate (ALR) was increased stepwise during the study period from 0.16 to 0.46 kg NH$_4$-N/m$^3$·d, as the HRT was decreased from 8 to 2.5 h. HRTs and ALR were directly related because the effluent ammonia concentration of the UASB reactor (influent of the JLR) was relatively constant (Fig. 9). Approximately 99.8 ± 0.1 and 98.5 ± 1.2% ammonia-nitrogen removal efficiency was achieved in the JLR at 8 and 5 h HRTs, leaving the final effluent with a mean NH$_4$-N concentration of approximately 0.11 ± 0.1 and 0.71 ± 0.6 mg NH$_4$-N/L, respectively (Fig. 10). The JLR, at an HRT of 8 and 5 h, on an average removed 94.0 ± 0.6 and 95.4 ± 1.3% of TKN, producing a final effluent with a mean TKN concentration of 3.5 ± 0.4 and 2.9 ± 0.9 mg/L, respectively (Fig. 11). Nitrogen balance showed that more than 90% of the TKN was converted into nitrate (Fig. 13). Only trace amounts of nitrite were produced. Based on the nitrogen mass balance, approximately 5, 5, 10 and 5% of the influent TKN was used in the synthesis of biomass at HRT of 8, 5, 3 and 2.5 h, respectively. With average influent TKN concentration of 60 mg/L, at all HRTs, these percentages correspond to 3, 3, 6 and 3 mg/L, respectively. Average influent BOD concentrations were 30, 35, 40 and 45 (with negligible effluent fBOD) at HRTs of 8, 5, 3 and 2.5 h, respectively. These translate into BOD/N ratios of 10, 12, 7 and 15, respectively, which was well below the typical BOD/N ratio of 20 for nutrient requirement of conventional activated sludge process. Low percentage of nitrogen utilized for biomass growth in the current study was possibly due to the low influent BOD concentration and dynamic MLSS in the JLR.

The results indicated that the JLR exhibited a high performance of ammonia-nitrogen and TKN removal, at HRTs of 8 and 5 h. This could be attributed to the conditions maintained in the JLR with an average F/M ratio of 0.27 ± 0.1 to 0.66 ± 0.3 kg COD/kg MLVSS·d, pH = 7 to 7.5, ORP = 170 to 230 mV, OLR of 0.21 ± 0.04 to 0.26 ± 0.02 kg COD/m$^3$·d, and SRT = 2 to 11 d (Fig. 14–17). These values are considered favourable for nitrification in the aerobic systems. Moreover, the venturi aeration system in the JLR promotes efficient oxygen
transfer (DO level of 2–6 mg/L) and excellent mixing conditions between biomass and substrate. These values are considerably higher than the reported DO affinity for ammonia oxidizers (0.3 mg O2/L) and nitrite oxidizers (1.1 mg O2/L) (Wiesmann 1994). The aeration of the reactor was increased by adjusting the JLR recycle pump flow, as the oxygen requirement per volume of reactor increased with higher ALR. Accordingly, the continuous sludge recycle flow rate was increased from 0.8 to 1.8 L/min on day 76. As a result, DO concentration in the JLR was increased from 2.35 to 5.30 mg/L.

Excessive biomass washout occurred on day 197 due to some mechanical problems. Consequently, the throat of the venturi was partially plugged and DO concentration and ORP dropped sharply. Ammonia-nitrogen removal efficiency also decreased to less than 10%. Operation of the JLR was stopped and a new venturi was installed. The reactor recovered quickly despite the ammonia-nitrogen removal efficiency of only 26%.

Ammonia-nitrogen removal efficiency decreased from 99.8 ± 0.1 to 28.0 ± 7.1% at higher organic loadings, ALR and F/M ratios, as shown in Fig. 11 and 12. Also, the TKN removal decreased from 94.0 ± 0.6 to 27.3 ± 1.8%. The relatively short HRTs and SRTs (see Table 3) were not favourable for nitrification because the autotrophic nitrifiers are slow-growing bacteria and are washed out at low SRTs. Grady et al. (1999) reported that a minimum SRT of 3 to 18 d is required to provide complete nitrification.

Comparisons of the JLR with other Ammonia Removal Systems

Table 4 presents a comparison of the ammonia-nitrogen removal efficiency achieved by different suspended-growth and attached-growth systems receiving low-strength effluent from the UASB reactor at different

<table>
<thead>
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<th>Parameter (n = 5)</th>
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<td>HRT (h)</td>
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</tr>
<tr>
<td>5.0</td>
</tr>
<tr>
<td>3.0</td>
</tr>
<tr>
<td>2.5</td>
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</table>
HRTs. As indicated, the JLR outperformed the attached-growth systems such as HSCP and RBC with higher HRTs. Shorter HRTs can be achieved in attached-growth systems due to detainment of bacterial cells on the biofilms, which increases the sludge age. However, it was reported that the attached-growth systems pose several disadvantages such as biofilm clogging and larger space requirements (Gonçalves et al. 1998). The JLR had higher ammonia-nitrogen removal efficiency when compared to the SBR at relatively same HRTs, temperature, organic loading rate and ammonia loading rate. The results indicate that the JLR can be considered as an aerobic post-treatment alternative.

Conclusions

The study concluded that decreasing the HRTs (and increasing the OLRs) of the integrated system simultaneously resulted in a reduction of the overall organic removal efficiency of the JLR. However, it was found that on average more than 87% of total BOD and COD and more than 95% of filtered BOD and COD were removed from the integrated UASB-JLR system at the overall system HRTs of 18, 11, 7 and 5.5 h. The JLR can be considered as an effective post-treatment system for treating the UASB effluent, with an overall ammonia-nitrogen removal efficiency of 99.8 and 98.5%, at HRTs of 8 and 5 h, respectively. Inconsistent performance by the JLR could be of concern because of the dynamic MLSS concentrations and poor settleability due to high shear force exerted by the venturi.

References


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### TABLE 4. Ammonia-nitrogen removal in other reactors

<table>
<thead>
<tr>
<th>Reactors</th>
<th>HRT (h)</th>
<th>NH₄-N removal (%)</th>
<th>Effluent NH₄-N (mg/L)</th>
<th>References</th>
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<td>4</td>
<td>85</td>
<td>n/a</td>
<td>Souza and Foresti (1996)</td>
</tr>
<tr>
<td>HSCP</td>
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<td>75</td>
<td>8</td>
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<td>RBC</td>
<td>3–10</td>
<td>&gt;80</td>
<td>3.3–10.6</td>
<td>Tawfik et al. (2001)</td>
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<tr>
<td>HSCP</td>
<td>2</td>
<td>18</td>
<td>28</td>
<td>Tandukar et al. (2004)</td>
</tr>
<tr>
<td>JLR</td>
<td>5–8</td>
<td>&gt;99</td>
<td>&lt;1</td>
<td>Present study</td>
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