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Continuous fill intermittent decant type sequencing batch reactor application to upgrade the UASB treated sewage

Abid Ali Khan · Rubia Zahid Gaur · Vasileios Diamantis ·
Beni Lew · Indu Mehrotra · A. A. Kazmi

Abstract The performance of continuous flow intermittent decant type sequencing batch (CFID) reactor treating the effluent of an UASB reactor treating domestic wastewater and operated at 8 h hydraulic retention time (HRT) was investigated. The CFID was operated at three different HRTs (22, 8 and 6 h) and three different dissolved oxygen (DO) patterns (<0.5, 2.5–3.5 and 3.5–4.5 mg/L). The highest effluent quality was observed at the 8 h HRT and 2.5–3.5 mg/L DO concentration. At this operational condition, the average BOD, TSS, ammonia nitrogen and fecal coliform removal efficiencies were 83, 90, 74 and 99 %, respectively. The CFID is a promising post-treatment option for existing UASB systems, with a final effluent quality that comply with receiving water and effluent reuse criteria.

Keywords Dissolved oxygen limitation · Hydraulic retention time · Upflow anaerobic sludge blanket · Sequencing batch reactor · Ammonia removal

A. A. Khan (✉) · R. Z. Gaur · I. Mehrotra · A. A. Kazmi
Department of Civil Engineering, IIT Roorkee,
Roorkee 246447, India
e-mail: dee.abid@gmail.com

V. Diamantis
Department of Environmental Engineering,
Democritus University of Thrace, Xanthi, Greece

B. Lew
The Volcani Center, Institute of Agriculture Engineering,
Beit Dagan 50250, Israel

B. Lew
Department of Civil Engineering, Ariel University Center
of Judea and Samaria, Ariel 40700, Israel

Introduction

The upflow anaerobic sludge blanket (UASB) technology has been widely accepted for the treatment of sewage in a number of developing countries [1–3]. However, the effluent quality never complies with standards for water discharge or effluent reuse. Therefore, a post-treatment system is always required in order to reduce the organics and suspended matter to permissible limits.

In order to achieve the required effluent quality, a variety of post-treatment methods based on diverse combinations with UASB treatment have been investigated including, trickling filter (TF) [4], rotating biological contactor (RBC) [5, 6], submerged aerated bio-filter (SABF) [7, 8], dissolved air flotation (DAF) [9], down flow hanging sponge (DHS) [10], sequencing batch reactor (SBR) [11–13], wetlands [14], activated sludge process (ASP) [15, 16], polishing ponds [17] and recently studied flash aeration system [2, 18]. While a few systems, such as aerated lagoons, polishing ponds, wetlands and ASP have been tested in full scale, the majority remain mostly under investigation at laboratory and pilot scale, claiming to be a viable post-treatment option. Based on extensive review of literature, between these systems, the SBR has been pointed to be the most promising solution for polishing the effluent of UASB reactor treating sewage [1, 2]. The system has been investigated by different authors for the removal of residual COD and TSS from the UASB effluent. The overall removal efficiencies of COD and TSS were observed from 91 to 89 % [11–13]. However, all SBR studied so far are of the batch type and no research on continuous flow SBR has been conducted so far for the treatment of UASB effluent. The continuous flow intermittent decant type SBR can be a better option for treatment of effluent of UASB reactor due to continuous supply of substrate during non-aeration period for the denitrification in a cyclic operation.

The primary focus of present study is the removal of residual organics, suspended solids, ammonia nitrogen and coliform from effluent of UASB reactor using laboratory scale activated sludge in continuous flow intermittent decant (CFID) reactor.

Methods

UASB reactor

The pilot scale UASB reactor had dimensions of 0.2×0.2 m internal base with 1.5 m in height giving an effective volume of 45 L (Fig. 1). The reactor was operated at a fixed hydraulic retention time (HRT) of 8 h using actual sewage obtained from a pumping station of Roorkee town, India. The UASB reactor was inoculated with 15 L well adapted anaerobic seed sludge. The seed sludge was collected from a 38-million-liters/day (MLD) UASB based STP situated at Saharanpur, India ($29°55'48.60''$N and $77°30'41.34''$E). After inoculation, the average TSS and VSS concentrations in the reactor were 24.4 and 10.9 g/L, respectively. The specific methanogenic activity (SMA) and sludge volume index (SVI) of seed sludge were 0.03 g CH_4-COD/g VSS.day and 20 mL/g, respectively. To overcome the interference of ambient temperature, the UASB reactor was initially placed inside a chamber maintained at 32 ± 3 °C and operated at organic load of 0.180 g COD/L/day, based on the guidelines given by Lettinga et al. (1981) [19]. Startup period was around 3 weeks. Afterwards, the reactor was operated at 8 h HRT for about 3.5 years.

Continuous flow intermittent decant (CFID) reactor

The CFID reactor had a base dimension of 500×300 mm and a variable height level (~ 313, 300 and 225 mm) to attain different operational HRTs (h). The reactor was operated with sequences of aeration, settle and decant with continuous inflow from the UASB effluent (Fig. 1). After aeration and settling, supernatant was gravity removed (decanted) through a flow controlled 12 mm diameter pipe to simulate the variable volume operation of a full scale reactor. Effluent was received and accumulated daily in order to provide representative and composite 24 h samples.

During aeration, air was introduced through nine fine porous ceramic stone diffusers at the bottom of the reactor from a 53 psi, 135 L/min air pump and the reactor was mechanically mixed (double paddle, 100–150 rpm) in order to maintain constant DO conditions all over the reactor.

The CFID reactor was operated at six different regimes as summarized in Table 1. Aeration sequencing was standardized at half the total cycle time for each case study.

Case study I and II, each of 240 SBR cycles were conducted in sequence; case III following a gap of about 15 days was conducted over 360 SBR cycles. Case IV was conducted over 120 SBR cycles after which case V and VI followed in sequence over 300 and 250 SBR cycles, respectively.

Analytical procedure

The oxidation reduction potential (ORP) and the biogas produced in the UASB reactor were monitored to verify the operational stability of the system. UASB redox was checked with an ORP electrode (Aqua Lytic, Model E-27006-21) by comparing and standardizing with the redox potential of ZoBell's solution.

The CFID influent and effluent was daily monitored for temperature, pH, Alkalinity, chemical oxygen demand (COD) and ORP, whereas sulfates, total sulfides, NH_4-N, NO_3-N, PO_4-P and biological oxygen demand (BOD) were determined twice a week. Total suspended solids (TSS), volatile suspended solids (VSS), sludge volume (SV_{30}) and

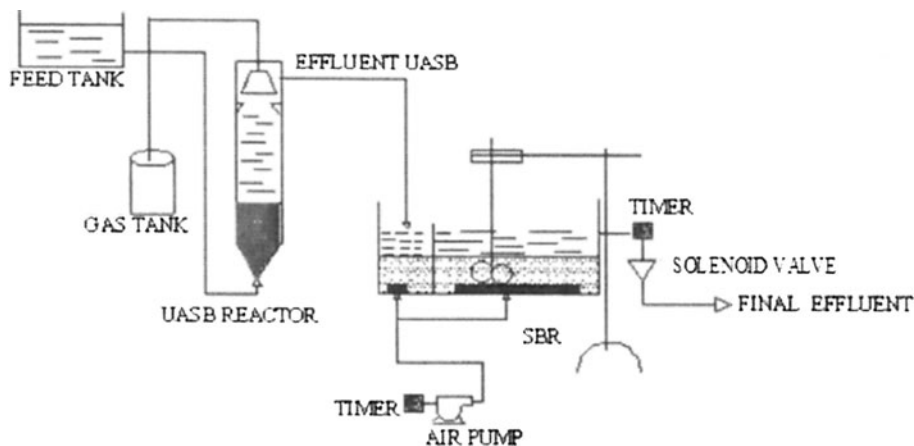**Fig. 1** Schematic representation of the UASB–CFID reactor

Table 1 Operating conditions for the CFID reactor

Case of Study	HRT (h)	DO level (mg/L)	Study period (days)	No. of data points (n)	Cycle duration (h)	Aeration (h)	Settling (h)	Decantation (h)	F/M (gm BOD/g MLVSS. Aerated day)
I	20	4.0–5.0	30	25	8	4	3.0	1.0	0.06–0.14
II	20	<0.5	20	14	8	4	3.0	1.0	0.06–0.14
III	8	2.5–3.5	90	70	6	3	2.0	1.0	0.1–0.64
IV	8	<0.5	30	20	6	3	2.0	1.0	0.14–0.24
V	6	2.5–3.5	75	60	4	2	1.5	0.5	0.2–0.64
VI	6	<0.5	50	42	4	2	1.5	0.5	0.22–0.82

fecal coliform densities were measured weekly. Moreover, representative concentrations of different parameters (COD, NH_4-N, NO_3-N and PO_4-P N) was conducted every half hour during a whole cycle, twice for each study case at days 8, 41, 100, 155, 200 and 275.

All wet analyses were performed according to Standard Methods of Examination of Water and Wastewater [20].

Results and discussion

UASB performance

UASB influent and effluent parameters are summarized in Table 2, which shows values of the range, mean and standard deviation of the different parameters concentration.

The mean percentage removal of BOD, COD and TSS in UASB reactor varied between 60–70 %, 60–65 % and 60–65 %, respectively. This performance is similar to that reported for well working full scale facilities in India [2]. The removal of nitrogen and phosphorus was not significant, as expected and; the effluent pH remained within the optimal working range for anaerobic digestion (6.9–7.9) throughout the experimental program.

CFID reactor: long term operation

The UASB effluent with the concentration mentioned in Table 2 was fed to the CFID reactor. At the different CFID operating conditions, the final treated effluent concentrations are summarized in Table 2. The BOD and COD removal efficiencies in the CFID (Table 2) varied from 78 to 87 % and 70 to 85 %, respectively, at the different study condition, indicating that the COD and BOD removal were not significantly affected by HRT, DO and cycle time. Still, the highest BOD removal was observed for case study III, IV, V and VI. Ozer et al. [21] also reported similar COD removals for different cycle times in a SBR reactor.

The effluent BOD concentration average was lower than 20 mg/L for all the cases studied, with almost no variation in the concentration value, even with the high variation in HRT and influent BOD concentration. This observation indicates that the system can cope with organic load fluctuations and would be sufficiently stable under full scale conditions. Still, the discharge limit of less than 15 mg/L BOD was not reached for the operation modes II, IV and VI.

The TSS removal efficiency under all operating conditions in CFID ranged from 70 to 80 %, resulting in a total 80 to 95 % TSS removal in the UASB-CFID system (Table 2). The considerable fluctuation in TSS concentration in the sewage (150–450 mg/L) was fully dampened by the UASB and the relatively low mean concentration of TSS in the effluent (<32 mg/L) suggests the presence of an adequately flocculent biomass in the reactor.

A similar and high ammonia removal (Table 2) was observed in study cases I, III and V (>2.5 mg/L DO), 70 %. In other case studies (<0.5 mg/L DO) a lower ammonia removal was observed, 42, 21 and 60 % for cases II, IV and VI, respectively, indicating that the ammonia removal was mainly dependent on DO concentration.

Although DO concentration played a major factor in ammonia removal, temperature variation did not appear to affect ammonia removal provided the DO was non-limiting (results not showed).

Denitrification was occurring in the reactor at both DO regimes, however, at higher rates for the high DO conditions (cases I, III and V) due to the fact that high nitrate concentrations were formed (in the nitrification process) in the high DO study cases.

The influent CFID PO_4-P was low, around 5–8 mg/L (Table 2) and a low removal was also observed for all cases study. The small fraction of phosphorus removed reflects assimilation by cell growth, since the reactor operational conditions did not favor enhanced biological phosphorus removal.

Sludge characteristics

The variation of sludge SV_{30}, MLSS and MLVSS with time in the CFID is shown in Fig. 2. Sludge settling characteristics (SV_{30} values) reinforce the assumption of the presence of an adequately flocculent biomass in the

Table 2 Performance of integrated UASB–CFID system for sewage treatment at different operating conditions

Parameters	Influent and effluent concentration of UASB reactor						CFID effluent concentration (mg/L) Under different set of study			
	Influent (sewage)	Mean	SD	UASB effluent	Mean	SD	I Mean	I SD	II Mean	II SD
COD (mg/L)	200–650	435	102	88–213	149	46	39	32	24	5
BOD (mg/L)	89–350	228	72	46–102	70	19	17	18	13	4
TSS (mg/L)	60–450	360	172	104–273	172	71	32	14	18	5
T-N (mg/L)	23–158	72	16	20–150	70	20	29	6	42	19
NH_4-N (mg/L)	22–153	55	15	15–145	65	19	28	6	40	18
NO_3-N (mg/L)	0.30–7.0	3.5	2.0	4.0–10.0	4	2	1.3	0.9	2.2	0.6
PO_4-P (mg/L)	2–10	9.15	4.26	7.82–11.2	9.12	1.15	3	1	5	1
FC MPN/100 mL	4.3E+05	4.3E+05	4.3E+05	4.3E+04–4.3E+05	1.89E+05	2.10E+05	2.12E+03	1.84E+03	1.2E+03	8.20E+02

Parameters	CFID effluent concentration (mg/L) Under different set of study							
	III Mean	III SD	IV Mean	IV SD	V Mean	V SD	VI Mean	VI SD
COD (mg/L)	24	12	20	4	22	12	17	12
BOD (mg/L)	9	6	6	1	12	9	9	7
TSS (mg/L)	26	12	27	8	16	8	14	7
T-N (mg/L)	21	11	57	12	23	13	29	12
NH_4-N (mg/L)	17	11	55	11	17	13	24	11
NO_3-N (mg/L)	0.98	0.55	2	0.44	6	3	5	2
PO_4-P (mg/L)	9	7	3	1	4	5	4	0.3
FC MPN/100 mL	1.80E+03	1.94E+03	1.58E+03	9.05E+02	1.75E+03	1.71E+03	1.34E+03	9.04E+02

SD standard deviation, *FC* fecal coliform

Fig. 2 Operating Conditions for MLSS, MLVSS and SV$_{30}$ at different case studies
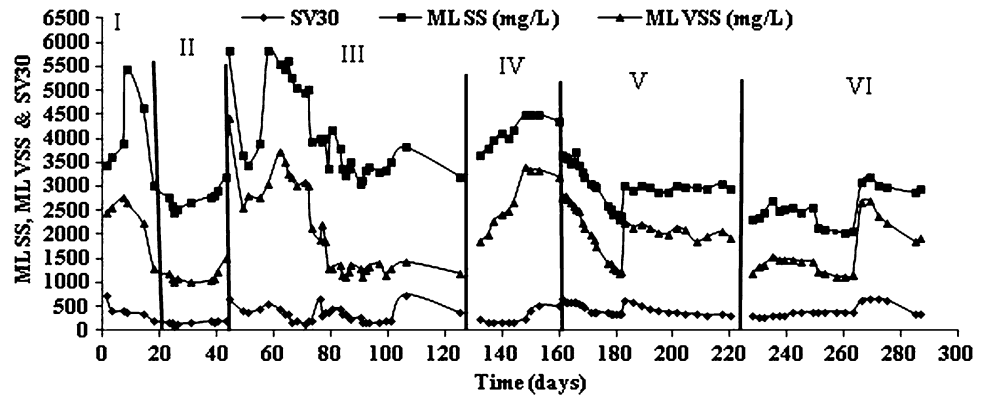
reactor, particularly for study conditions where the settling time was longer than 90 min. A decrease in MLVSS was observed in all cases studies due to the sludge re-acclimation, low organic loading and the relative over aeration, especially during the high DO reaction conditions. The loss of volatiles through endogenation exceeded the metabolic yield because of the low strength of the influent substrates leading to a decrease of the volatile fraction.

Biomass settling characteristics was generally a reflection of varying reaction conditions that took place under the low organic loading and the different DO regimes of this screening study.

Nitrification and denitrification during CFID cycle operation

At each case study ammonia and nitrate concentrations and alkalinity changes with time were determined in the first half-cycle operation (aeration, mixing and settling conditions), Fig. 3.

The operation under DO limiting conditions (<0.5 mg/L) clearly showed a suppression of nitrification and a negligible removal of NH$_4$-N (study cases II, IV and VI, Fig. 3) disregarding the HRT.

It has been previously observed that nitrifier's growth does take place at 0.5 mg/L DO [22] and that explains the negligible ammonia removal.

Under the operation of non-limiting DO conditions (>2.5 mg/L, study cases I, III and V) high nitrification rate constants of greater than 0.89 h^{-1} were observed.

Significant denitrification was observed to take place in the settled sludge layer for the non-limiting DO conditions, with best apparent removal in the 8 and 6 h cycles, even when the influent COD:TN ratio shows soluble carbon to be limiting.

Ammonia introduced during the non-aeration react sequencing is conservative and partly remains in the reactor for reaction in the subsequent aeration sequence and partly is removed hydraulically (bypassed) during the removal of the treated effluent. Ammonia bypass is related to the cycle time and fill ratio and; is a feature of CFID processing. Bypass can be addressed with proper design in which the organic loading and retention time are by necessity relatively low and high, respectively, and with limitation of the fill ratio. Bypass, as measured by NH$_4$-N, was essentially the same for all cycles and HRTs.

Spilling effect of influent species in CFID

Figure 4 shows the ammonia, nitrate, phosphate and COD concentration with time during the decanting in the different cases of study. All parameters concentration increased with time in all the cases studied, indicating part of the influent would be spilled (leave the reactor before treatment). The spilling effect was occurring due to the reactor modus of operation, continuous fill. Based on the increase in ammonia and COD concentration, it can be inferred that 10–20 % spilling was occurring. Phosphorous and nitrate were less affected by the spilling effect, probably because during decanting period anoxic conditions are present in the reactor and the introduction of organic matter led to nitrate consumption as the electron acceptor. Phosphorus influent concentration was low and probably it was utilized for cell growth.

Carbon mass balance in UASB–CFID system

The COD mass balance was applied to quantify the electron sinks in the investigated mechanisms. The sinks for the influent organic carbon in the substrate fed to UASB reactor were the biogas (methane and carbon dioxide), effluent, reduction with sulfates and biomass growth. The COD of the methane dissolved in the effluent (based on Henry's constant) was calculated by Henry's law (Eq. 1) by assuming partial pressure of methane 0.7 atm. The Henry's constant for methane gas $H_u = 28.13$ [23].
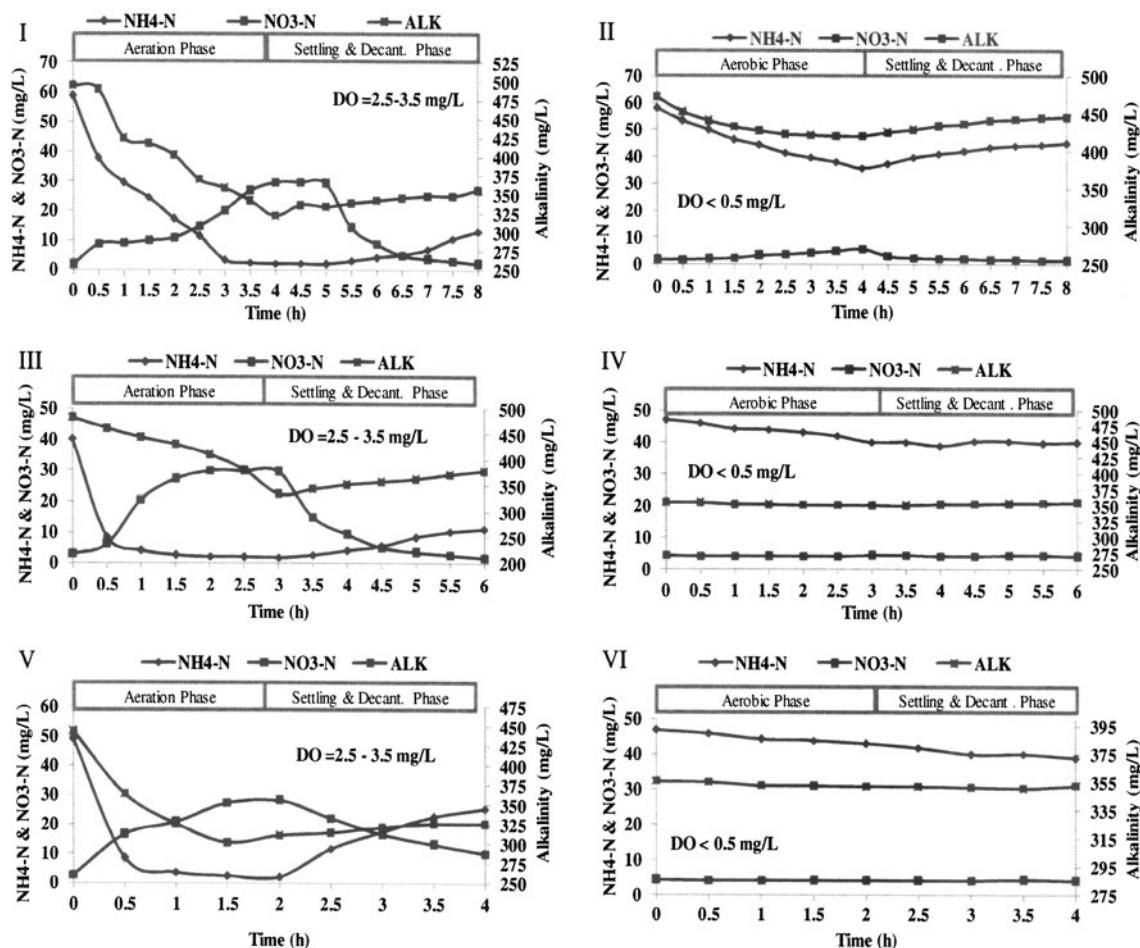
Fig. 3 Temporal Variation of NH₄–N, NO₃–N and alkalinity during complete cycles at the different study cases (I–VI)

Therefore, $H = H_u RT$ atm.m³/mole   (1)

Average partial pressure of methane in biogas
$= 70\%$ (assume)

Aqueous methane $(CH_4) = \dfrac{P_{CH_4}}{H_u RT}$ mole/m³

Aqueous $CH_4 - COD = 1.018 \dfrac{\text{mole}}{\text{m}^3} \times \dfrac{64 \text{ g COD}}{1 \text{ mole } CH_4}$

$\times \dfrac{1 \text{ m}^3}{1{,}000 \text{ L}}$ or dissolved $CH_4 - COD$

$= 65.13$ mg COD/liter of wastewater at 25 °C

The inflow and effluent COD mass in the UASB reactor were calculated based on the COD concentration and influent flow rate. CH₄–COD in biogas and was calculated according to Eq. (2).

$CH_4 - COD = (2.87 \times Y \times V \times 273)/(273 + t)$ (2)

where Y is the percentage of methane content in biogas, V is the volume of the biogas produced in liters, and t temperature in °C.

The mass of sulfate reduced to total sulfides also consumed COD in UASB reactor [24]. The sulfates COD must be accounted separately as this COD was not converted neither to methane nor into sludge, nor left in the effluent. Therefore, the COD consumed for sulfate reduction was calculated according to Eq. (3).

$S^{-2} + 2O_2 = SO_4^{2-}$ (3)

Whereas the mass of sulfate reduced must be multiplied by factor of 0.67 (64/96) to get the COD of sulfate reduced.

The biomass growth was assumed to be the remaining COD in the system, calculated by the subtraction of total outlet COD mass (effluent, COD present in the biogas and COD utilized for sulfide reduction) from inlet COD mass.

The COD reduction in aeration CFID basically depends on following mechanisms:

1. Immediate oxygen demand due to reduced species such as H₂S, HS⁻ and S²⁻ [24–27].
2. Volatilization/air stripping of purgeable organic compounds/VOCs [28].
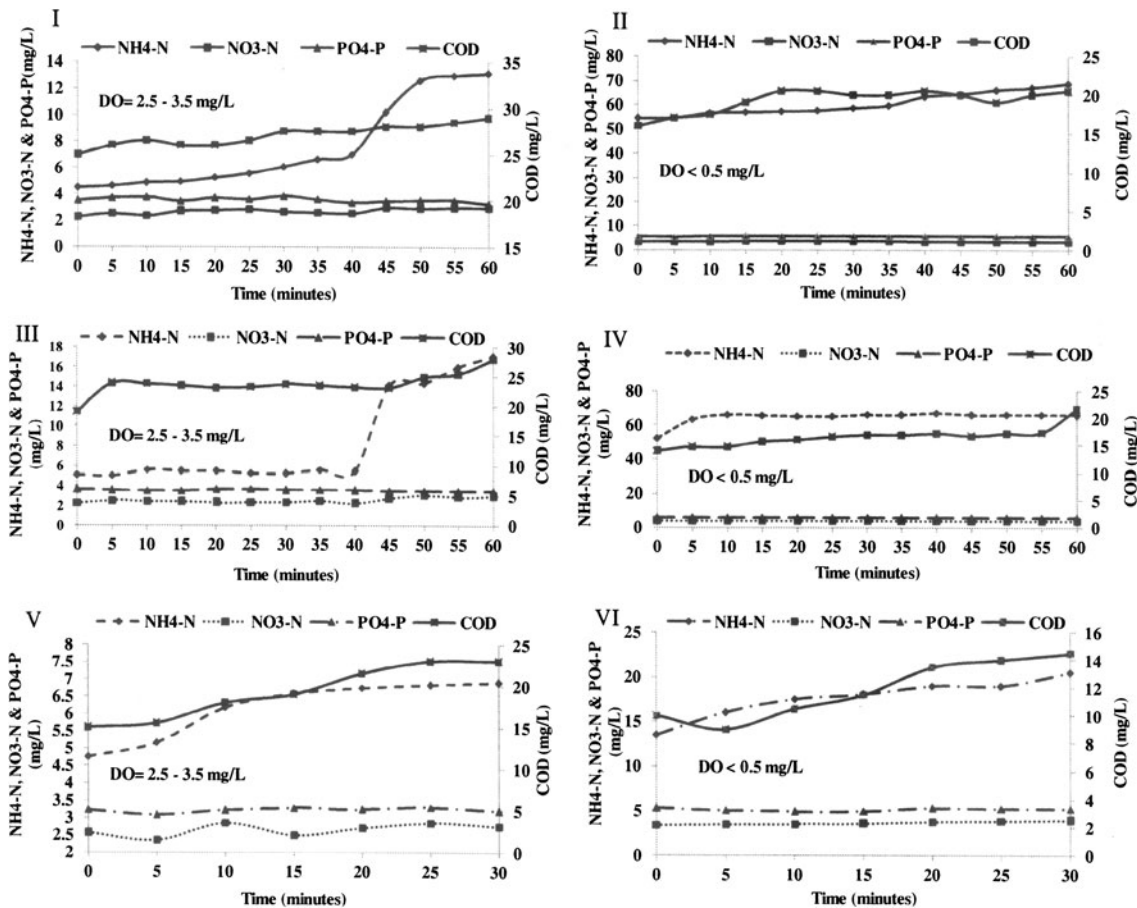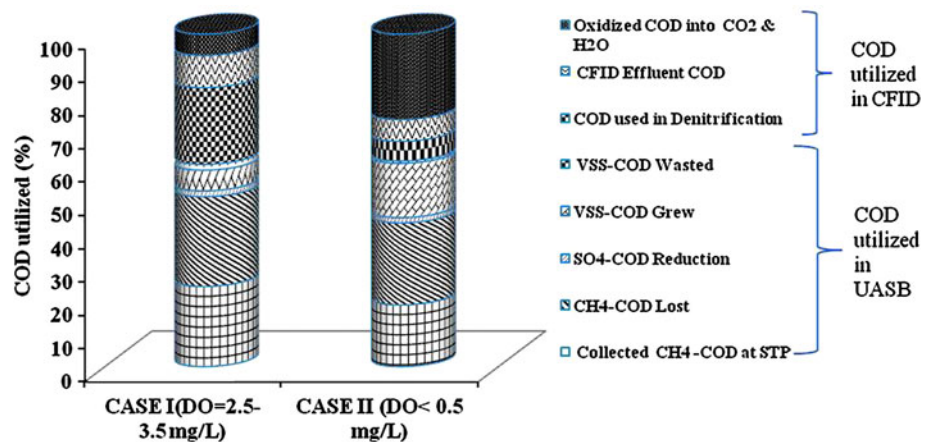3. Biological oxidation or SMP.

Fig. 4 NH$_4$–N, NO$_3$–N, PO$_4$–P and COD concentration with time during decantation in the different study cases (I–VI)

Fig. 5 COD mass balance in the UASB–CFID system

Whereas the sum of the above three is the oxygen demand in aeration. The carbon mass balance in the combined UASB–CFID system and calculated as previously explained, is showed in Fig. 5. The incoming carbon was mainly converted into biogas in UASB (around 44–55 %) and very small fraction was converted to the biomass growth (around 1.5–2 %). The carbon that was not

consumed in the UASB reactor, was present in the effluent and it was effectively utilized for denitrification during settling in the CFID at high DO conditions. Under limiting DO conditions, the carbon was mainly utilized through simply oxidation. Finally, the COD which spilled in the CFID effluent was very low during the whole reactor operation. The remaining COD can be regard as

non-biodegradable [29]. This fraction in fact is quite small, representing around less than 10 % of the COD initially coming to the combined system in sewage.

Conclusions

The CFID system can be a good alternative for the effluent treatment of an UASB reactor treating domestic wastewater. High BOD, COD, TSS, nitrogen and fecal coliform removals were observed, around 90 %, for a high range of F/M values, 0.05–0.32 day^{-1}. Reactor operation at the proper conditions can lead to an effective nitrification–denitrification. Results shows that the CFID effluents can meet receiving water and effluent reuse discharge criteria based on STPs. Full scale adaption of these results requires a design and configuration that properly manages inherent carbon limitation and ammonia leakage.

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