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ORIGINAL ARTICLE

Performance of Full-Scale UASB Reactors Treating Low or Medium Strength Municipal Wastewater

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Abstract Upflow Anaerobic Sludge Blanket (UASB) reactors treating low or medium strength municipal wastewater were monitored under field conditions in India. The study aimed to evaluate the efficiency of the UASB process (in terms of organics, solids and nutrients removal) and to highlight the causes and remedies for odour nuisances. The UASB reactors represent a robust and efficient technology for sewage pre-treatment (COD removal: 51%; BOD: 56%; TSS: 54%), capable to generate renewable energy (biogas yield: 0.20–0.40 m^3 kg^{-1} COD removed) under the conditions prevailing in India. The UASB performed significantly better when low strength wastewater (COD ~300 mg L^{-1}) was treated, giving a final effluent COD of around 120 mg L^{-1}, similar to aerobic treatment systems. In the case of medium strength municipal wastewater with high sulphate content (COD: 600 mg L^{-1}; SO_4: 175 mg L^{-1}), a 10-fold increase of the effluent sulphide concentrations was recorded (from 3 to 34 mg L^{-1}), compared to low strength sewage processing (from 1.5 to 7.0 mg L^{-1}). As such, major odour nuisances (release of H_2S) may originate from the anaerobic effluent itself, as well as from spontaneous biogas losses.

Keywords Sewage treatment · Anaerobic wastewater treatment · Full-scale UASB · Hydrogen sulphide · Sulphate reduction · Odour control

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1 Introduction

Upflow Anaerobic Sludge Blanket (UASB) reactors are widely used for municipal wastewater treatment (Chong et al. 2012; Sato et al. 2006). In India, forty four (44) UASB-based sewage treatment plants (STP) are currently in operation, having a total capacity of 2.6 million m^3 of wastewater per day (CPCB 2013). However, from unpublished source, seventy one (71) UASB-based STP existed in India till date, with many UASB reactors being either dysfunctional or in dismantle stage due to poor O&M. The UASB reactor can typically remove 40–70% of wastewater solids and organics, through combined physical (sedimentation, sludge bed filtration) and biological processes (anaerobic degradation) (Chernicharo et al. 2015). Simultaneously, heavy metals are precipitated as metal sulphides (Kiran et al. 2017) and several consistent micropollutants are degraded, such as caffeine, bisphenol and paracetamol (Yang et al. 2016; Froehner et al. 2011). Combined with an aerobic low-rate treatment system (e.g., trickling filter, constructed wetland, flash aeration), it can provide high degree of wastewater purification, with zero energy input and low excess sludge production (Alemu et al. 2016; Khan et al. 2012; Khan et al. 2011; Verstraete et al. 2009; Alvarez et al. 2008). In addition, the UASB reactor can recover biogas from sewage which is considered a renewable source of energy (Diamantis et al. 2016; Chernicharo et al. 2015).

One important feature of the anaerobic wastewater treatment systems is the formation of sulphides (Aiyuk et al. 2006). The latter are produced during the anaerobic reduction of sulphates and organic S compounds, originally present in municipal wastewater, by sulphate reducing bacteria (van den Brand et al. 2015). They often downgrade the quality of the biogas and the anaerobic liquid effluent, rendering them highly corrosive and malodorous. The concentration of sulphides in the liquid effluent of municipal UASB reactors is reported to be between 20 and 30 mg L^{-1}, while the hydrogen sulphide (H_2S) content in the biogas varied from 1000 to 4000 ppm (Noyola et al. 2006). Different technologies for controlling or minimizing the concentration of sulphides in anaerobic wastewater treatment systems include limited aeration or nitrates supplementation, and post-treatment of the generated biogas and the anaerobic liquid effluent by physical, chemical and/or biological processes (Krayzelova et al. 2015; Abatzoglou and Boivin 2009; Cirne et al. 2008). Thus, it is possible to minimize odour nuisances which are of major concern for sewage treatment plants neighbouring with residential areas.

In the present study, ten (10) full-scale UASB reactors in India were surveyed and monitored under actual operating conditions with emphasis on process performance (removal of COD, BOD, TSS; sulphate reduction and biogas production). The aim of the study was to evaluate the efficiency of the UASB technology treating low or medium strength municipal wastewater, and to highlight the causes and remedies for odour nuisances, under the conditions prevailing in India.

2 Materials and Methods

2.1 UASB Reactor Monitoring

Ten (10) full-scale UASB reactors treating municipal wastewater were surveyed and monitored under actual operating conditions. The wastewater treatment plants of the city of Agra, Karnal, Saharanpur, Surat, Vadodara, Noida (Sector-50 and Sector-54) and Ludhiana (Bhattian, Balloke and Jamalpur) were examined during the course of this study. Process efficiency of the full-scale UASB reactors was assessed by sampling and characterization of influent and effluent wastewater samples under summer and/or winter conditions prevailing in India. Sewage temperature was relatively constant and fluctuated between 18 and 23 and 26–29 °C during winter and summer conditions, respectively. Ambient concentrations of H_2S were determined at different locations at the site of two (2) wastewater treatment plants (Ludhiana and Noida) reported for major odour nuisances, both receiving wastewater with high sulphate content. The basic design parameters of the full-scale UASB facilities are summarized in Table 1.

2.2 Analytical Methods

Samples obtained from the wastewater treatment plants were immediately transported to the laboratory and analyzed for COD, BOD, TSS, NH_4-N, PO_4-P, sulphates (SO_4^{2-}) and sulphides (S^{2-}) according to Standard Methods (APHA 1998). Soluble COD and BOD concentrations were determined after sample filtration with 0.45 μm membrane filters. Ambient concentrations of H_2S were measured using a portable H_2S meter (model no. Pac 5500, Drager Co. USA). The concentrations of sulphide-oxygen demand were calculated using the stoichiometry Eq. (1) and (2).

$$S^{2-} + 2O_2 \rightarrow SO_4 \qquad (1)$$

$$HS^{-} + {}^{1}/{}_{2}O_2 \rightarrow S^{o} + OH^{-} \qquad (2)$$

3 Results and Discussion

3.1 UASB Reactor Performance

The sewage from different wastewater treatment plants of India was characterized as low or medium strength, based on the concentrations of COD, BOD and TSS (Metcalf and Eddy 2003). At Agra, Karnal and Saharanpur (low strength sewage), the concentrations of COD, BOD and TSS were on average 309 ± 51, 173 ± 35 and 229 ± 78 mg L^{-1} respectively, with a particulate COD fraction of 48 ± 7%. At Noida, Ludhiana, Surat and Vadodara (medium strength sewage), the respective COD, BOD and TSS values were equal to 605 ± 134, 251 ± 75 and 454 ± 248 mg L^{-1}, with a particulate COD fraction of 62 ± 16%. The concentrations of phosphorus (PO_4-P) were not significantly different in low or medium strength sewage and approached 5.6 ± 2.4 mg L^{-1}. Conversely, the ammonia nitrogen content displayed a slight increase from 37 ± 11 to 46 ± 29 mg L^{-1}, in accordance with municipal wastewater strength. The detailed dataset of municipal wastewater characteristics from different UASB based treatment plants can be found in Table 2.

Figure 1 presents the concentrations of COD, BOD, TSS, sulphides, ammonia and phosphorus at the influent and effluent of municipal UASB reactors, treating both low and medium strength wastewaters. The examined parameters display good linear relationship with a regression coefficient (R^2) between 0.64 and 0.91. Indeed, process efficiency was stable and COD, BOD and TSS removal were 51 ± 13, 56 ± 11 and 54 ± 13%, respectively. These values

Table 1 Dimensions and design parameters of full-scale UASB reactors treating municipal wastewater in India

WWTP	Capacity (m^3 d^{-1})	Length (m)	Width (m)	Depth (m)	N	Total Volume (m^3)	HRT (h)	Surface (m^2)	Upflow velocity (m d^{-1})	Post-treatment
Agra	78,000	24	40	5.25	6	30,240	9.3	5760	13.5	Polishing pond
Karnal	40,000	32	24	4.8	4	14,746	8.8	3072	13.0	Polishing pond
Saharanpur	38,000	24	28	6.1	4	16,397	10.4	2688	14.1	Polishing pond
Surat	100,000	20	20	7.44	20	59,520	14.3	8000	12.5	Activated sludge
Vadodara	43,000	24	22	4.8	6	15,206	8.5	3168	13.6	Activated sludge
Noida, Sector-50	27,000	24	28	6.1	3	12,298	10.9	2016	13.4	Polishing pond
Noida, Sector-54	34,000	24	24	6.25	4	14,400	10.2	2304	14.8	Polishing pond
Ludhiana, Bhattian	111,000	32	30	5.1	9	44,064	9.5	8640	12.8	Polishing pond
Ludhiana, Balloke	152,000	32	38	5.1	12	74,419	11.8	14,592	10.4	Polishing pond
Ludhiana, Jamalpur	48,000	32	30	5.1	4	19,584	9.8	3840	12.5	Polishing pond

N number of UASB reactors, *HRT* hydraulic retention time

Table 2 Database of influent and effluent wastewater characteristics from different UASB reactors in India

WWTP		UASB reactor influent											UASB reactor effluent										
		pH	Alk	COD	CODs	BOD	BODs	TSS	S^{2-}	SO_4	NH_4-N	PO_4-P	pH	Alk	COD	CODs	BOD	BODs	TSS	S^{2-}	SO_4	NH_4-N	PO_4-P
Summer campaign																							
Noida Sector 54	*n* = 1	7.22	530	539	253	187	130	398	4.0	255	69	4.6	7.34	620	274	198	84	77	132	69	39	87	5.5
Agra	*n* = 3	7.33	284	252	158	143	91	121	2.0	54	14.1	3.6	7.33	291	143	67	74	42	72	8,1	17	14.7	3.6
Vadodara	*n* = 3	7.47	336	566	191	150	98	386	0.0	98	21.9	4.0	7.13	314	139	61	57	31	114	22.7	23	38.8	5.2
Karnal	*n* = 3	7.37	328	296	118	170	94	151	2.8	58	52	9.0	7.50	296	111	51	68	34	58	7.6	14	59	9.1
Ludhiana Jamalpur	*n* = 3	7.55	537	796	226	183	115	791	2.0	121	17	2.4	7.19	399	667	200	102	98	386	17	75	23	3
Ludhiana Balloke	*n* = 3	7.39	505	547	256	356	236	894	2.4	228	29	6.9	7.32	637	245	185	148	122	452	30	55	37	7
Ludhiana Bhattian	*n* = 3	7.30	496	384	264	293	181	292	3.4	167	23	4.0	7.20	592	206	78	200	58	242	32	105	29	4
Saharanpur	*n* = 3	7.85	322	379	170	198	117	326	1.1	31	36	4.4	7.30	346	158	69	89	66	141	4.4	18	39	5.1
Winter campaign																							
Saharanpur	*n* = 3	7.27	327	220	118	101	69	151	0.9	48	31	4.8	7.33	289	98	55	51	30	58	4.8	35	37	4.1
Saharanpur	*n* = 2	7.30	322	329	173	198	90	299	0.0	47	41	5.3	7.00	343	150	90	80	47	120	5.7	22	48	5.6
Saharanpur	*n* = 3	7.35	350	325	185	187	108	294	1.5	39	36	5.6	7.22	359	121	76	72	42	104	7.9	14	54	5.8
Saharanpur	*n* = 2	7.00	326	346	170	198	105	172	2.3	44	43	4.3	6.99	355	157	61	68	40	79	8.2	15	49	4.9
Saharanpur	*n* = 3	7.27	350	321	170	186	102	271	1.5	42	40	5.8	7.30	355	143	67	74	42	100	8.0	17	56	5.7
Noida Sector 50	*n* = 3	7.22	-	756	202	341	163	361	3.4	174	93	10.0	7.33	-	450	113	159	81	146	36	38	90	11
Noida Sector 54	*n* = 3	7.12	-	566	100	242	80	274	5.3	266	77	11.0	7.45	-	277	78	50	41	128	37	146	81	15
Surat	*n* = 2	7.13	500	689	237	253	96.5	236	2.5	99.5	36	4.5	7.00	508	403	184	135	63.5	142	25.5	46.5	41	4.1

All units in mg L^{-1} except for alkalinity (Alk) (mg $CaCO_3$ L^{-1}) and pH; n = number of grab samples analyzed

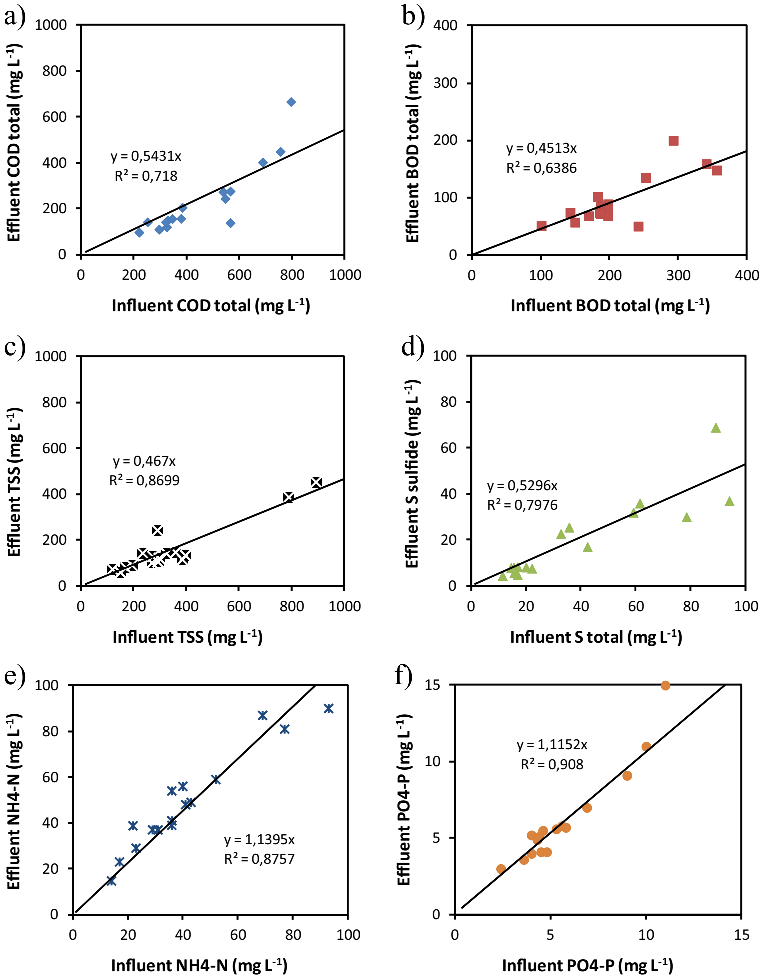

Fig. 1 Concentrations of: **a** COD, **b** BOD, **c** TSS, **d** sulphides, **e** ammonia, and **f** phosphorus, at the influent and effluent of municipal UASB reactors in India. Effluent sulphides concentration is expressed as a function of influent S total

are typical for one-step UASB reactors treating sewage (Abbasi and Abbasi 2012; Sato et al. 2006). Ammonia nitrogen, similarly to phosphates, displayed a slight increase by a factor of 1.1, due to protein mineralization. The concentrations of nutrients in the anaerobic effluent were considered beneficial in case of reusing them for irrigation/fertilization. This is, however, possible only after controlling the residual organics and pathogen contents, according to the local wastewater reuse legislation (Angelakis and Snyder 2015).

The organic loading rate (OLR) imposed on different full-scale UASB reactors varied from 0.74 ± 0.11 to 1.38 ± 0.33 kg m^{-3} d^{-1} for low and medium strength sewage, respectively. The OLR was mainly affected by the wastewater COD concentration, since the applied hydraulic retention times in these installations were very similar, in the range of 8–12 h (see Table 1). Accordingly, the biogas production rate followed the imposed OLR values. In Vadodara (medium strength sewage) the biogas production rate ranged between 150 and 235 m^3 h^{-1}, while in Karnal and Saharanpur (low strength sewage) it was between 130 and 197 and 90–130 m^3 h^{-1}, respectively. The above mentioned reactors were all of similar size (see Table 1) and the biogas yield corresponded to 0.20–0.40 m^3 kg^{-1} COD removed. These values are consistent with previous reports on UASB facilities treating municipal wastewater (Crone et al. 2016; Aiyuk et al. 2006). In Ludhiana (Balloke), however, the biogas yield was limited to 0.05–0.11 m^3 kg^{-1} COD removed, which was attributed to major biogas losses from the corroded pipelines. Biogas production data were not available at Agra, Surat, Noida (sector 50 and sector 54) and Ludhiana (Jamalpur) due to malfunction of the measuring equipment.

3.2 Sulphate Reduction and Odour Nuisances

Due to the presence of sulphates, the anaerobic degradation of organic matter proceeds partially via sulphate reduction (Krayzelova et al. 2015). The medium strength sewage exhibited significantly higher concentrations of sulphates (59 ± 23 mg S L^{-1}) compared to the low strength wastewater (15 ± 2 mg S L^{-1}), consequently the COD/SO_4 ratio was lower, viz. 4 ± 2 and 7 ± 3, respectively. The degree of sulphate reduction averaged 59 ± 17% and was not affected by the COD/SO_4 ratio (Fig. 1). Al-Jamal and Mahmoud (2009) obtained similar results when examined the efficiency of a UASB-septic tank for Palestinian sewage, and they concluded that sulphates decreased by 45–75% during the anaerobic digestion process.

The reduction of sulphates to sulphides can both increase the treated effluent COD/BOD values, and contribute to the release of H_2S (from the anaerobic effluent and the generated biogas), a severely malodorous compound with a threshold level of 0.5 ppb. The sulphide content at the influent and the effluent of the UASB reactors was 3.0 ± 1.6 mg L^{-1} and 34.0 ± 16 mg L^{-1} for medium strength, and 1.5 ± 0.9 and 7.0 ± 2.0 mg L^{-1} for low strength sewage, respectively. It can thus be concluded that the sulphide-oxygen demand is from 8 ± 3% up to 22 ± 6% in case of low and medium strength wastewaters, respectively (see Table 3). In the former case, the anaerobic effluent was characterized by an organic COD of 121 ± 22 mg L^{-1}, similar to aerobic biological treatment systems (Alemu et al. 2016).

Figure 2 presents the measured concentrations of H_2S in the ambient air at a number of positions at the Noida (Sector 54) and Ludhiana (Bhattian) wastewater treatment plants. Both

Table 3 Fractionation of COD, BOD and sulphur compounds at the influent and effluent of UASB reactors treating low or medium strength municipal wastewater

	Low strength sewage			Medium strength sewage		
Parameter	Influent (mg L^{-1})	Effluent (mg L^{-1})	Removed (%)	Influent (mg L^{-1})	Effluent (mg L^{-1})	Removed (%)
COD total	309 ± 51	135 ± 22	56 ± 6	605 ± 134	333 ± 168	47 ± 17
COD soluble	158 ± 26	67 ± 12	57 ± 5	216 ± 54	137 ± 60	36 ± 22
COD sulphide	3 ± 2	14 ± 3		6 ± 3	67 ± 32	
COD organic	305 ± 51	121 ± 22	60 ± 6	600 ± 135	265 ± 180	58 ± 19
BOD total	173 ± 35	72 ± 11	57 ± 6	251 ± 75	117 ± 53	54 ± 14
BOD soluble	97 ± 15	43 ± 11	56 ± 7	137 ± 53	71 ± 30	47 ± 18
BOD sulphide	0.8 ± 0.4	3.4 ± 0.8		1.4 ± 0.8	18 ± 8	
BOD organic	172 ± 35	69 ± 11	59 ± 6	249 ± 75	100 ± 54	61 ± 16
S total	17 ± 3	13 ± 2	19 ± 13	62 ± 24	56 ± 20	7 ± 17
S sulphate	15 ± 3	6 ± 2	57 ± 16	59 ± 23	22 ± 14	61 ± 20
S sulphide	2 ± 1	7 ± 2		3 ± 2	34 ± 16	

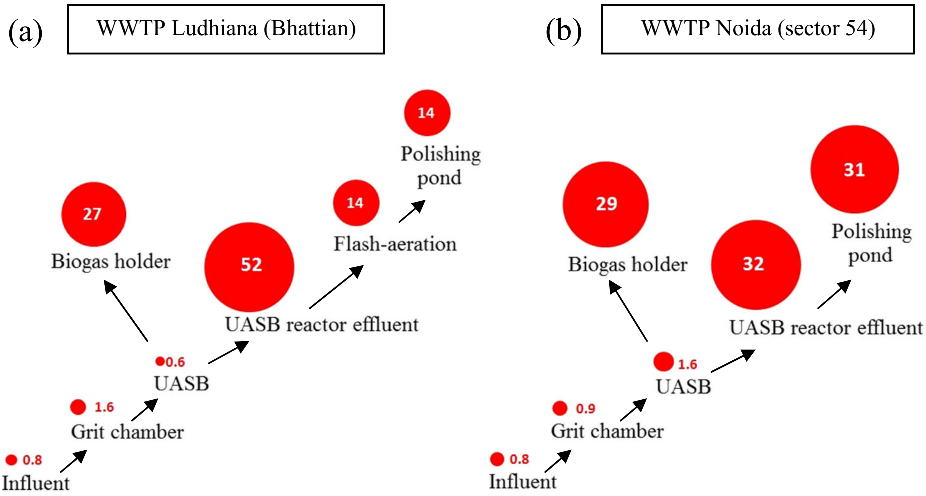

Fig. 2 Maximum ambient concentrations of H_2S (in ppm) recorded at different locations at the site of UASB-based wastewater treatment plants of India: **a** Ludhiana (Bhattian), and **b** Noida (Sector 54)

plants receive sewage with high sulphate content. The H_2S level at the grit chamber and on top of UASB reactors was always less than 2 ppm. However, high concentrations of H_2S were recorded near the biogas holder (up to 29 ppm), which was attributed to spontaneous biogas losses from corroded pipes and pressure relief devices. Despite the fact that all UASB reactors were equipped with biogas scrubbers, these were not functioning satisfactorily at most of the sites, rendering the released biogas a major source of malodour (H_2S).

Similarly, high concentrations of H_2S were recorded at the UASB reactors effluent (see Fig. 2), i.e., up to 52 ppm, which was attributed to the release (stripping) of H_2S, due to turbulent flow in open pipes. Considering the above, it is important to decrease the sulphide content from the UASB reactor liquid effluent. In the case of Ludhiana (Bhattian) wastewater treatment plant, this was accomplished by an aerobic oxidation process. The latter consisted of an aeration tank, equipped with mechanical surface aerators, and designed with a hydraulic retention time of 10 min. Post-aeration of the anaerobic effluent can decrease the concentration of sulphides by a combined process of stripping and bio-oxidation (Khan et al. 2012). As such, the ambient H_2S concentrations around the Ludhiana polishing ponds (1–14 ppm) were significantly lower compared to Noida (2–31 ppm), where the post-aeration process was not implemented (see Fig. 2). It is obvious that the oxidation process can be improved significantly; an optimal tackle would be to apply the innovative high-rate micro-aerobic treatment option in which sulphide is converted into elementary sulphur (Krayzelova et al. 2015). The latter method is even more attractive regarding its feature to remove colloidal matter from the anaerobic effluent, where the overall efficiency may increase to 70–80% for COD and BOD.

4 Conclusions

Full-scale UASB reactors treating municipal wastewater achieved constantly a removal efficiency of 51 ± 13% for COD, 56 ± 11% for BOD and 54 ± 13% for TSS, while ammonia and phosphorus were entirely recovered in the effluent. The UASB process in terms of effluent quality was significantly improved when low strength sewage was treated. In the case of medium strength wastewater with high sulphate content, special attention should be given for sulphide removal from the anaerobic liquid effluent. Proper operation and maintenance of the biogas equipment (piping, scrubber, biogas holder, and pressure relief devices) is also a prerequisite in order to avoid spontaneous biogas losses.

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