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Treatment of textile dyeing wastewater using two-phase pilot plant UASB reactor with sago wastewater as co-substrate

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ABSTRACT

Textile dyeing industry is considered as one of the largest generators of toxic chemical wastewater in India. Wastewaters from textile dyeing industries were studied for the decolourization and removal of degradable organics with tapioca sago wastewater as a co-substrate in a pilot scale two-phase Upflow Anaerobic Sludge Blanket (UASB) reactor. The UASB reactor was inoculated with seed sludge from the anaerobic digester treating sago wastewater. The colour and COD removal efficiency was studied by feeding the combined wastewater of sago and textile dyeing industry at different mixing proportion (90:10, 80:20, 75:25, 70:30, 65:35) with COD ranging from 5200 to 6320 mg L^{-1}. The maximum COD removal was about 53.1% in acidogenic reactor (90:10 mixing ratio) and 88.5% in methanogenic reactor (70:30 mixing ratio). In methanogenic reactor at organic loading rate of 5.6 kg COD/m^3 d maximum COD (88.5%) and colour (91.3%) removal were achieved. The value of VFA/alkalinity ratio at the outlet of methanogenic reactor was less than 0.08, proves the process stability of the reactor. The maximum biogas production in methanogenic reactor was achieved at 70:30 mixing ratio.

1. Introduction

The generation of highly coloured wastewater by the textile dyeing industry now-a-days constitutes an important environmental problem. In 1978, it was estimated that around 2% of the 450,000 tons of dyes produced in the world were discharged as trade effluents, whereas around 9% were discharged in textile dyeing effluents [1]. The colour in textile dye-house effluent and the possible problems associated with the discharge of dyes and dye degradation products are of environmental concern [2]. The release of coloured compounds into water bodies is undesirable because of their impact on photosynthesis of aquatic plants, the carcinogenic nature of many of these dyes and their break-down products [3]. Whereas in case of sago effluent possesses high COD, highly acidic and highly organic in nature. As a result of discharge of sago wastewater depletion of dissolved oxygen is imported in the water sources of the affected area. It also causes an increase in air pollution in terms of stringent foul odour, inorganic carbon deposit and change of soil matrix.

Several combinations of treatment methods have been developed in order to effectively process textile wastewater, decolourization being one among them. For simplification, the treatment can be classified into chemical, physical, and biological treatment. Physical and chemical methods are costly, less efficient, have limited application and also generate huge quantities of sludge as solid wastes which are difficult to dispose off [2]. Microbial decolourization and degradation of dye is a cost-competitive alternative to chemical decomposition processes [4]. One of the anaerobic methods available for treating both textile dye-house effluent and sago effluent is Upflow Anaerobic Sludge Blanket (UASB) reactor. UASB reactors belong to the group of high-rate anaerobic reactors with a sludge bed. Granular biomass with high methanogenic activity and excellent settling properties can be cultivated in these reactors [5]. The limitations of UASB reactors are related to the wash-out of biomass. In the present investigation, textile dye-house effluent and tapioca sago wastewater at various proportions was deployed. Advantage of combining the effluents was the pH gets neutralized, therefore no need of adding caustic/lime. Similarly, the presence of starch in the sago industry wastewater reduces the addition of nutrients during the process. The sago effluent was utilized as co-substrate to enhance the degradation of textile dye-house effluent which is recalcitrant in nature. This paper deals with the performance of pilot scale two-phase UASB reactor at different mixing ratio (90:10, 80:20, 75:25, 70:30, 63:35) of sago effluent and textile dyeing wastewater respectively.

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Table 1
Characteristics of wastewaters.

S. no.	Parameters[a]	Textile dyeing wastewater	Sago wastewater
1	pH	12.8	4.5
2	Total suspended solids	420	640
3	Total dissolved solids	3520	1200
4	Chlorides	1520	400
5	Sulphates	180	123
6	BOD	175	2400
7	COD	1600	6000

[a] All values except pH are in mg L^{-1}.

2. Materials and methods

2.1. Biomass

The methanogenic granular sludge with unknown microorganisms used in this experiment was procured from the anaerobic digester treating sago effluent at M/s Perumal SAGO factory, Salem, Tamilnadu, India. Before loading the reactor, granular sludge was clearly washed, filtered through a fine mesh ASTM 16 to remove all floating and suspended contents. The volatile suspended solids content of the sludge was estimated as per the standard methods and found to be 60,000 mg L^{-1} [6].

2.2. Wastewater

Real untreated wastewater from sago industry and textile dyeing industry was collected at Salem, Tamilnadu, India. Ten samples were collected from each industry for duration of three months and the mean values of the parameters are given in Table 1. The analysis of the wastewater was carried out according to standard methods [6].

2.3. Experimental setup

In order to study the operational and performance characteristics of UASB reactor, a hybrid two-phase UASB reactor was fabricated (Fig. 1). The acidogenic and methanogenic reactors were fabricated with 1:4 volumetric ratios. The first phase was an acidogenic reactor (300 mm inner diameter and 820 mm height) made up of plexi-glass with working volume of 56 L and second phase was a stainless steel methanogenic reactor (350 mm inner diameter and 2400 mm height) with working volume of 230 L. The untreated real effluent was fed into the acidogenic reactor followed by methanogenic reactor. Sampling ports were provided at a spacing of 400 mm throughout the height of reactor. The Gas–Liquid–Solid Separator (GLSS) was attached at top of the reactor, consisted of an inverted conical funnel at top of the water column for the collection of biogas. In addition to the GLSS arrangement, a packed medium consisting of a PVC spirals with size of 26 mm, surface area 500 m^2 m^{-3} and void ratio 87% has been provided for a height of 200 mm located at 1770 mm from the bottom of the reactor. These spirals will retain the biomass as well as gives a polishing effect to the effluent. The sludge granules trapped in GLSS and the packed media± will return to the reactor as soon as the gas entrapped inside the granules was released. Biogas generated was measured using wet gas flow meter. After stabilizing the reactor, studies were conducted under the steady state conditions. At steady state the rate of change of input to output does not change with time and also the consistent in COD removal and maintenance of VFA/alkalinity ratio as less than 0.4 shows the steady state condition. The reactor was operated under room temperature (28 ± 5 °C) at different mixing ratios (90:10, 80:20, 75:25, 70:30 and 65:35) of sago and textile dyeing wastewater with an Organic Loading Rate (OLR) of 6.32, 6.16, 6.0, 5.6 and 5.2 kg COD/m^3 d respectively. Since the two phases of the reactor was designed on the volumetric ratio of 1:4, the acidogenic and methanogenic reactors were operated at a Hydraulic Retention Time (HRT) of 6 and 24 h respectively. The pH, TDS and temperature of both the reactors were monitored by Programmable Logic Control (PLC) system continuously for every 15 min.

2.4. Analytical procedures

The treated and untreated samples were analyzed for pH, COD and colour removal, VFA and alkalinity as per Standard Methods

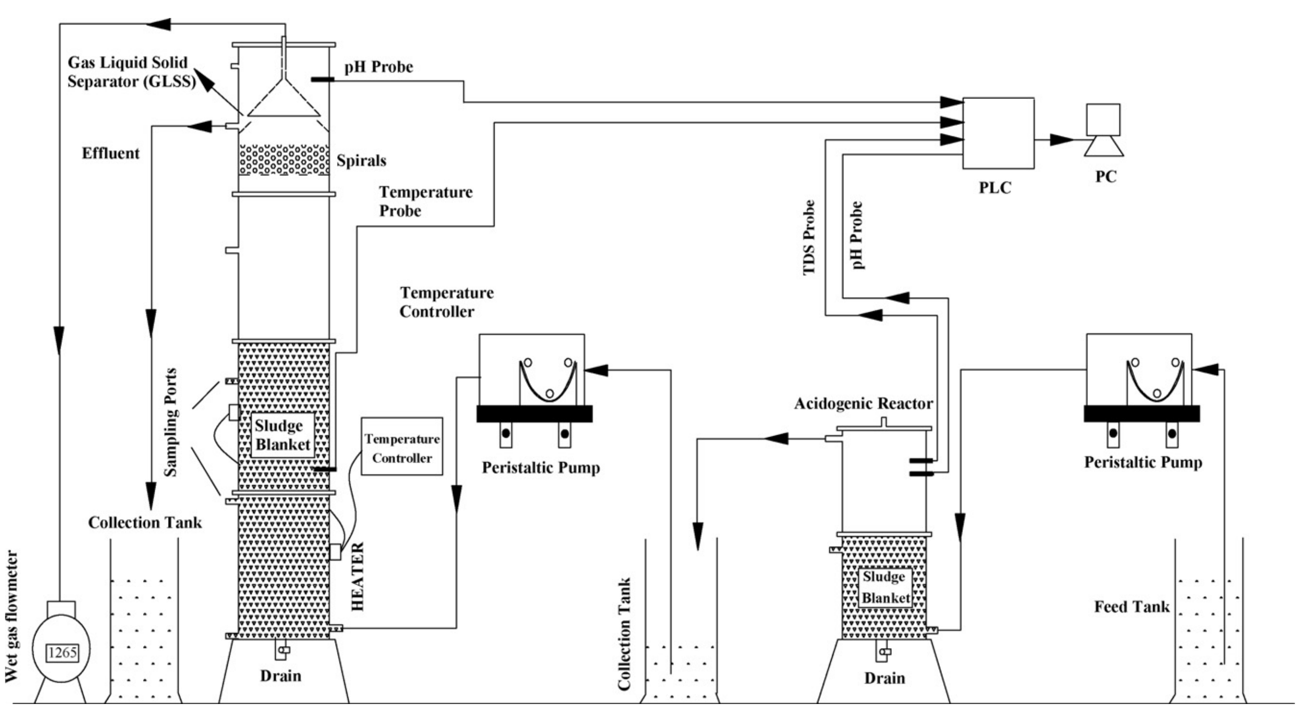

Fig. 1. Schematic diagram of two-phase UASB reactor.

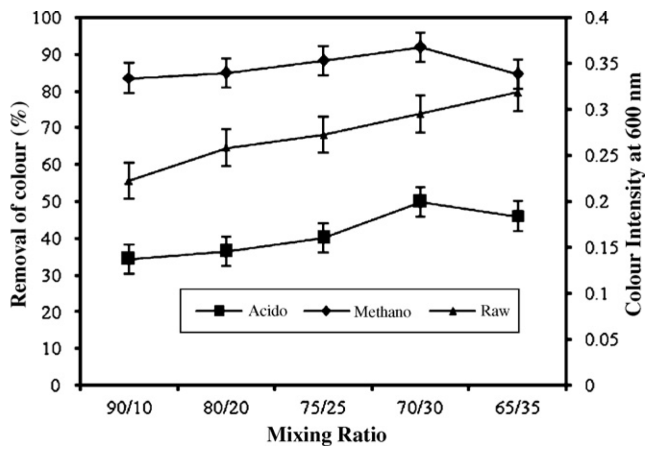

Fig. 2. Colour intensity of the raw effluent and colour removal of acidogenic and methanogenic reactor at different mixing ratios.

for Examination of Water and Wastewater [6]. Colour removal was estimated by monitoring the Optical Density (OD) of the samples using UV–vis spectrophotometer (HITACHI–U2001) at 600 nm. COD was measured by using closed reflux titrimetric method. VFA and Alkalinity was also estimated by titrimetric method. Before analysis, all samples were filtered through 0.45 mm filters to remove suspended matters.

3. Result and discussion

Among the high rate anaerobic reactors the UASB reactor are more efficient. The success of the UASB reactor depends on its capability to retain a high concentration of immobilized active biomass which is capable of treating high strength wastewater.

3.1. Colour removal

Colour intensity of combined wastewater was measured spectrophotometrically at 600 nm in terms of OD and found to be 0.222, 0.258, 0.272, 0.295 and 0.318 for different mixing ratio 90:10, 80:20, 75:25, 70:30, 65:35 and 60:40 respectively (Fig. 2). Fig. 2 shows the colour intensity of the raw effluent and percentage of colour removal at various stages of the process. In acidogenic reactor, the colour removal efficiency was in the range of 34.2–49.8% and in the methanogenic reactor the overall colour removal efficiency was in the range 83.4–91.8%. The colour removal efficiency remains almost stable ranging from 83.4 to 89.4% for the initial mixing ratios (90:10; 80:20; 75:25) and a maximum of 91.8% was achieved at the mixing ratio of 70:30. The reactor was stable in colour removal till the 70:30 ratio beyond that the percentage of colour removal was reduced. Thus the presence of various types of dyes at low concentrations in the influent initially not affected the metabolism of dyes. At high concentration (65:35) the toxicity of the dye effluent may affect the metabolism. Further at high concentration the dye may bind over the surface of the granule and reduce its efficiency. Senthilkumar et al. [7] achieved 97.0% of colour removal in a 15 L capacity bench scale two-phase UASB reactor treating a synthetic combined textile dyeing and sago wastewater at 12 h HRT. The colour removal from acid dyeing textile wastewater using laboratory scale UASB reactor having a capacity of 2.5 dm^3 with 17 HRT was reported with an efficiency of 81.0–96.0% [8]. Carliell et al. [9] and Razo-Flores et al. [10] reported that 90.0% of decolourization of reactive and azo dyes using strictly anaerobic methane forming bacteria. Thus the present process is more efficient in colour removal by utilizing another waste namely sago wastewater.

3.2. COD conversion and removal performance

Table 2 shows the COD of the raw effluent, acidogenic reactor and methanogenic reactor outlets. COD concentration of raw effluent vary between 6320 and 5200 mg L^{-1}, acidogenic outlet vary from 2960 to 4000 mg L^{-1} and for methanogenic outlet vary from 640 to 1200 mg L^{-1}. With increase in the percentage of textile dyeing wastewater from 90:10 to 65:35 (sago:textile dyeing wastewater) the COD of raw effluent decreased from 6320 to 5200 mg L^{-1} this is due to the low COD of textile effluent. The COD removal efficiency for different effluent mixing proportions at 6 and 24 h HRT of acidogenic and methanogenic reactor respectively is presented in Fig. 3. In acidogenic and methanogenic reactors the COD removal efficiency was in the range of 23.0–53.0 and 81.0–88.5% respectively. A wide range (23.0–53.0%) of COD removal efficiency was noticed in acidogenic phase due to a wide variation of pH (5.7–7.9) of the various mixing ratios of effluent. At lower concentration of textile dyeing wastewater, pH value of combined wastewater is low, VFA conversion is faster and COD removal is high. Similarly at higher concentration of dye, pH value of combined wastewater becomes higher and COD removal decreases. Whereas, in methanogenic phase the inlet effluent entering from acidogenic reactor have a very consistent pH range between 6.4 and 6.8 which are favourable for methanogens. Hence the COD removal efficiency of methanogenic reactor was a very narrow range of 81.0–88.5%. Thus the higher COD removal of 88.5% was achieved at the optimum mixing ratio of 70:30 (sago:textile dyeing wastewater). In order to improve the COD removal, the system can be operated for a longer HRT or an aerobic process can be provided after anaerobic as a polishing step. Senthilkumar et al. [7] reported 96.0% of COD removal in a 15 L capacity bench scale two-phase UASB reactor treating a synthetic combined textile dyeing and sago wastewater at 12 h HRT. Bras et al. [11] achieved a maximum COD removal of 90.0% at 96 h HRT with the maximum influent COD of 3000 mg L^{-1} in a bench scale UASB reactor treating synthetic monoazo and diazo dye. The efficiency of bench scale UASB reactor of 1.25 L in reducing COD was to be over 90.0% on treating real textile dyeing wastewater with initial COD concentration of 2000 mg L^{-1}[12].

3.3. Biogas

The biogas generation is directly related to type of substrate given as feed to the reactor. Table 2 point out the biogas production (312 L/d) was high in 70:30 mixing ratio. The biogas production for other mixing ratios 90:10, 80:20, 75:25 and 65:35 were 226, 286, 288 and 198 L/d respectively. The biogas production was sud-

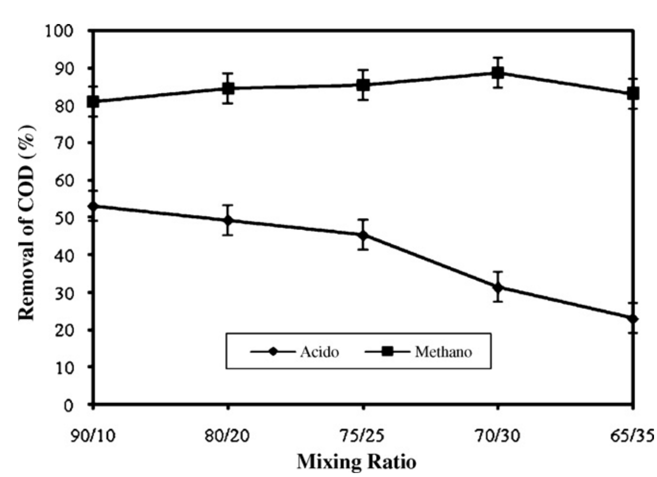

Fig. 3. COD removal at different mixing ratios.

Table 2
Parameters monitored during the process.

Mixing ratio of real wastewater (%)		HRT (h)	COD (mg L^{-1})			VFA (mg L^{-1})		Alkalinity (mg L^{-1})		Biogas (L/d)
Sago	Textile dyeing		Raw	Acido	Methano	Acido	Methano	Acido	Methano	
90	10	24	6320	2960	1200	788	72	424	926	226
80	20	24	6160	3120	960	738	84	456	935	286
75	25	24	6000	3280	880	744	60	502	987	288
70	30	24	5600	3840	640	728	56	566	966	312
65	35	24	5200	4000	880	722	40	594	998	198

denly decreases at the mixing ratio of 65:35 due to inhibitory effect of textile dyeing wastewater. The COD stabilization in reactor is directly related to biogas evolution, which decreases the COD of outlet wastewater from the reactor and provides the mechanisms for stabilization of the biodegradable organic matter. Talarposhti et al. [13] achieved a maximum biogas production of 160 L/g COD conversion treating simulated textile dyeing wastewater using two-phase anaerobic packed bed reactor.

3.4. Effect of OLR on COD and colour removal

The COD removal efficiency for different OLR at 24 h HRT is presented in Fig. 4. The COD removal efficiency in acidogenic and methanogenic reactor at different OLR ranging from 6.32 to 5.2 kg COD/m^3 d with respect to the mixing ratio of 23.0–53.0 and 81.0–88.5% respectively. The maximum COD and colour removal achieved at 5.6 kg COD/m^3 d was 88.5 and 91.8%. As the organic loading rate decreases from 6.32 to 5.6 kg COD/m^3 d with corresponding mixing ratio 90:10 to 70:30, the COD and colour removal increases from 81.0 to 88.5% and 59.4 to 91.8%. Whereas from the organic loading rate 5.6–5.2 kg COD/m^3 d, the COD and colour removal decreases due to inhibition of higher concentration of the textile dyeing wastewater in the feed (mixing ratio of 65:35). Gnanapragasam et al. [14] achieved 96% of COD removal at a OLR of 6.81 kg COD/m^3 d in a UASB reactor using real combined wastewater of textile dyeing and sago industries with recycling the treated wastewater. Talarposhti et al. [13] reported that the biodegradable COD decreased from 100 to 24.0% as the COD loading rate was increased from 0.25 to 1 kg COD/m^{3}d. Sandhya et al. [15] reported that the efficiency of COD removal decreases with the increase in OLR.

3.5. VFA and alkalinity under different mixing ratio

The Volatile Fatty Acid (VFA) and alkalinity of the acidogenic and methanogenic reactor under different mixing ratios are shown in Table 2. The VFA in acidogenic and methanogenic reactor varies between 722–788 and 40–84 mg L^{-1} respectively. The VFA for acidogenic reactor decreases as the percentage of textile dyeing wastewater increases in the feed. This low value is due to the increase in the proportion of high alkaline textile dyeing wastewater. For all the mixing ratios, VFA in the outlet of methanogenic reactor was less than 100 mg L^{-1} indicates the stability of reactor. Speece [16] also reported that for a stable operation of a reactor the VFA concentration should be less than the critical limits (250 mg L^{-1} as acetic acid). The alkalinity of acidogenic and methanogenic reactor for different mixing ratio was 456–566 and 926–998 mg L^{-1} respectively. Alkalinity of the acidogenic reactor was less than the methanogenic reactor due to higher production of fatty acids in this reactor. The fatty acid formation was decreased and the alkalinity level in the acidogenic reactor was increased as the percentage of textile dyeing wastewater increases in raw effluent. The stability of the methanogenic reactor was represented by the level of alkalinity in methanogenic reactor (900 mg L^{-1} for all mixing ratios). The present process is more advantages due to buffering action of textile dyeing wastewater.

3.6. VFA/alkalinity ratio under different mixing ratio

The VFA and alkalinity separately is not a good indicator for evaluating the process stability of the anaerobic reactor, since total alkalinity reflects both level of VFA and bicarbonate. Under unstable conditions increase in VFA reduced the bicarbonate resulting in constant total alkalinity. So the ratio of VFA to alkalinity is the best option to monitor process stability in anaerobic systems. The changes in VFA to alkalinity ratio for acidogenic and methanogenic reactor at different mixing ratios are presented in Fig. 5. The VFA/alkalinity ratios were 1.3–1.6 for acidogenic reactor outlet throughout the process, indicates the acid production in acidogenic reactor. The outlet VFA/alkalinity ratios of methanogenic reactor were ranging from 0.04 to 0.08 for different mixing ratios indicates the stable operation of methanogenic

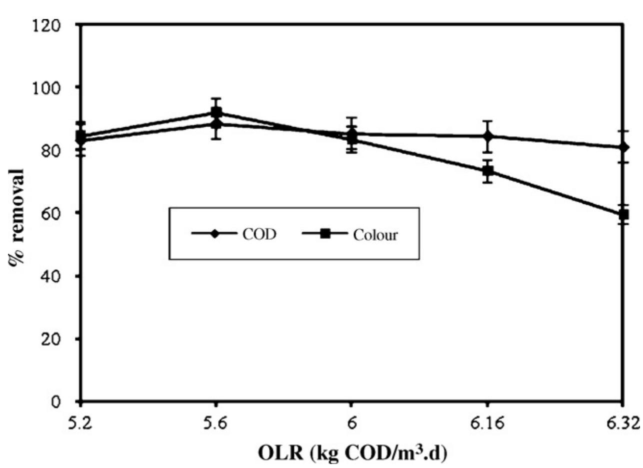

Fig. 4. COD and colour removal at different OLRs.

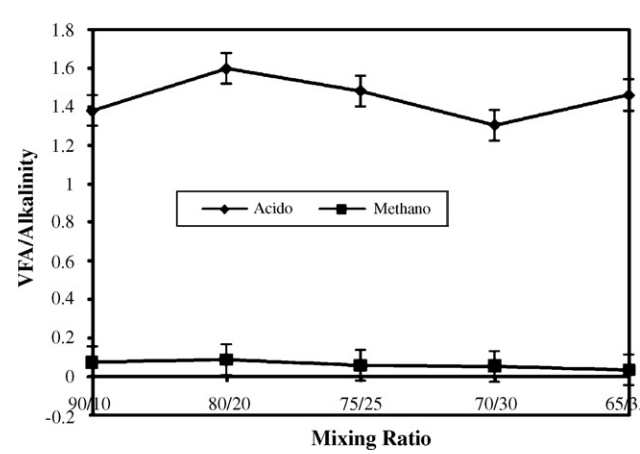

Fig. 5. VFA/alkalinity ratios at different mixing ratios.

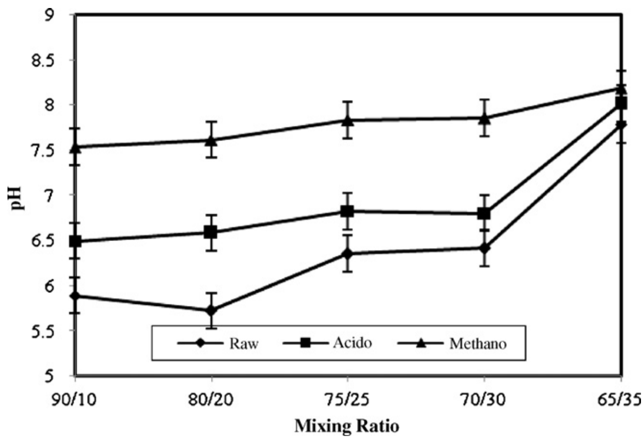

Fig. 6. Variations of pH at different mixing ratios.

reactor. Simpson [17] reported that the VFA/alkalinity ratio must be of very low range for stable anaerobic digester. Parkin et al. [18], Jaganathan et al. [19] and Isik [20] reported that VFA/alkalinity ratio should be less than 0.4 for the stable operation of anaerobic reactor.

3.7. pH changes

The pH are integral expression of the acid based condition of any anaerobic treatment process as well as intrinsic index of the balance between the two of the important microbial groups (acidogens and methanogens) [21,22]. The pH of the raw effluent, acidogenic and methanogenic outlet are shown in Fig. 6. The pH of raw effluent increases with increase in the percentage of textile dyeing wastewater, this occurs due to high alkaline nature of the textile dyeing wastewater. Thus the overall pH in both acidogenic and methanogenic reactors were increased. Initial pH of the raw effluent, acidogenic reactor outlet was 5.7–7.4 and 6.4–6.8 respectively (upto 30% mixing ratio). The pH gets increased to 8 for further increase the percentage of textile dyeing wastewater. The pH at methanogenic reactor outlet was in the range of 7.5–8.2. It should be noted that for a stable operational performance of anaerobic reactor the pH should be in the range of $6.5 < pH < 8.2$ [23,24].

4. Conclusion

The results of this study indicate that biphasic UASB reactor could be a very feasible alternative, eco-friendly and sustainable treatment system for textile dyeing effluent with sago effluent as a co-substrate, produce very less organic sludge. The maximum COD and colour removal efficiency achieved was 88.5 and 91.8% respectively at 24 h HRT at optimum mixing ratio of 70:30 (sago:dye wastewater). The maximum biogas production was 312 L/d at a rate of 0.42 L Biogas/g COD for a mixing ratio of 70:30 (sago:dye wastewater). The optimum OLR was 5.6 kg COD/m^3 d from different OLRs with respect to mixing ratios. The VFA/alkalinity ratio at optimum mixing ratio was 0.04 which indicates that the reactor is under stable condition.

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References

[1] C. O'Neill, F.R. Hawkes, D.L. Hawkes, N.D. Lourenzo, H.M. Pinheiro, W. Deleé, Colour on textile effluents—sources, measurement, discharge consents and simulation: a review, J. Chem. Technol. Biotechnol. 74 (1999) 1009–1018.
[2] X. Chen, Z. Shen, X. Zhu, Y. Fan, W. Wang, Advanced treatment of textile wastewater for reuse using electrochemical oxidation and membrane filtration, Water SA 31 (1) (2005) 127–132.
[3] J.H. Weisburger, Comments on the history and importance of aromatic and heterocyclic amines in public health, Mutat. Res. 506/507 (2002) 9–20.
[4] P. Verma, D. Madamwar, Decolourization of synthetic dyes by a newly isolated strain of *Serratia marcescens*, World J. Microbiol. Biotechnol. 19 (2003) 615–618.
[5] A.P. Buzzini, I.K. Sakamoto, M.B. Varesch, E.C. Pires, Evaluation of the microbal diversity in an UASB reactor treating from an unbleached pulp plant, Process Biochem. 41 (1) (2006) 168–176.
[6] American Public Health Association (APHA), Standard Methods for the Examination of Water and Waste Water, 20th ed., APHA, Washington, DC, USA, 2005.
[7] M. Senthilkumar, V. Arutchelvan, V. Kanakasabai, K.R. Venkatesh, S. Nagarajan, Biomineralisation of dye waste ina two-phase hybrid UASB reactor using starch effluent as a co-substrate, Int. J. Environ. Waste Manage. 3 (3/4) (2009) 354–365.
[8] I. Mustafa, T.S. Delia, Anaerobic/aerobic sequential treatment of a cotton textile mill wastewater, J. Chem. Technol. Biotechnol. 79 (2004) 1268–1274.
[9] C.M. Carliell, S.J. Barclay, N. Naidoo, C.A. Buckley, D.A. Mulholland, E. Senior, Microbial decolorization of reactive azo dye under anaerobic conditions, Water SA 21 (1) (1995) 61–69.
[10] E. Razo-Flores, M. Luijten, B. Donlon, G. Lettinga, H. Field, Biodegradation of selected azo dyes under methanogenic conditions, Water Sci. Technol. 32 (6–7) (1997) 65–72.
[11] R. Bras, A. Gomes, M.I.A. Ferra, H.M. Pinheiro, I.C. Gonclaves, Monoazo and diazo decolourization studies in a methanogenic UASB reactor, J. Biotechnol. 115 (2005) 57–66.
[12] W. Somasiri, W. Ruan, L. Xiufen, C. Jian, Evaluation of the efficacy of upflow anaerobic sludge blanket reactor in removal of colour and reduction of COD in real textile wastewater, Bioresour. Technol. 99 (2008) 3692–3699.
[13] M.A. Talarposhti, T. Donnelly, K. Anderson, Colour removal from a simulated dye wastewater using a two phase anaerobic packed bed reactor, Water Res. 35 (2) (2001) 425–432.
[14] G. Gnanapragasam, M. Senthilkumar, V. Arutchelvan, P. Sivarajan, S. Nagarajan, Recycle in upflow anaerobic sludge blanket reactor on treatment of real textile dye effluent, World J. Microb. Biotechnol. 6 (3) (2010) 1093–1098.
[15] S. Sandhya, K. Sarayu, K. Swaminathan, Determination of kinetic constants of hybrid textile wastewater treatment system, Bioresour. Technol. 99 (2008) 5793–5797.
[16] R.E. Speece, Anaerobic Biotechnology for Industrial Wastewater, Archae Press, Nashville, Tennessee, USA, 1996.
[17] J.R. Simpson, Some aspects of bio-chemistry of anaerobic digestion in wastewater treatment, in: P.C.G. Issac (Ed.), Waste Treatment, Pub Pergamon Press, Oxford, 1960, pp. 31–51.
[18] G.F. Parkin, W.F. Owen, The fundamentals of anaerobic digestion of wastewater sludges, J. Environ. Eng. 112 (1986) 867–920.
[19] J. Jeganathan, G. Nakhla, A. Bassi, Novel Hybrid PBR-UASB system for the treatment of high strength pet food wastewater, in: WEFTEC, 2006, pp. 5040–5048.
[20] M. Isik, Efficiency of simulated textile wastewater decolourisation process based on the methanogenic activity of upflow anaerobic sludge blanket reactor in salt inhibition condition, Enzyme Microbiol. Technol. 35 (2004) 399–404.
[21] S. Venkatamohan, N. Chandarasekararao, K. Krishnaprasad, P. Muralikrishnan, R. sreenivasrao, P.N. Sharma, Anaerobic treatment of complex chemical wastewater in sequencing batch biofilm reactor (AnSBBR): process optimization and evaluation of factor iteractions using Taguchi Dynamic DOE methodology, Biotechnol. Bioeng. 90 (2005) 732–745.
[22] J.F. Malina, F.G. Pohland, Anaerobic sludge digestion, in: Design of Anaerobic Process for the Treatment of Industrial and Municipal Wastes, Technomic Publishing Co. Inc., Lancaster, Basel, 1992.
[23] K.V. Rajeshwari, M. Balakrishnan, A. Kansal, K. Lata, U.V.N. Krishore, Renew. Sust. Energy Rev. 4 (2000) 135–156.
[24] W. Somasiri, W. Ruan, L. Xiufen, C. Jian, Decolourization of textile wastewater containing acid dyes in UASB reactor system under mixed anaerobic granular sludge, Electron. J. Environ. Agric. Food Chem. 5 (1) (2006) 1224–1234.