International Journal of Environmental Science and Technology (2022) 19:10325–10336
https://doi.org/10.1007/s13762-021-03830-0

ORIGINAL PAPER

Performance evaluation of integrated anaerobic and aerobic reactors for treatment of real textile wastewater

Integrated anaerobic and aerobic reactors for textile wastewater treatment

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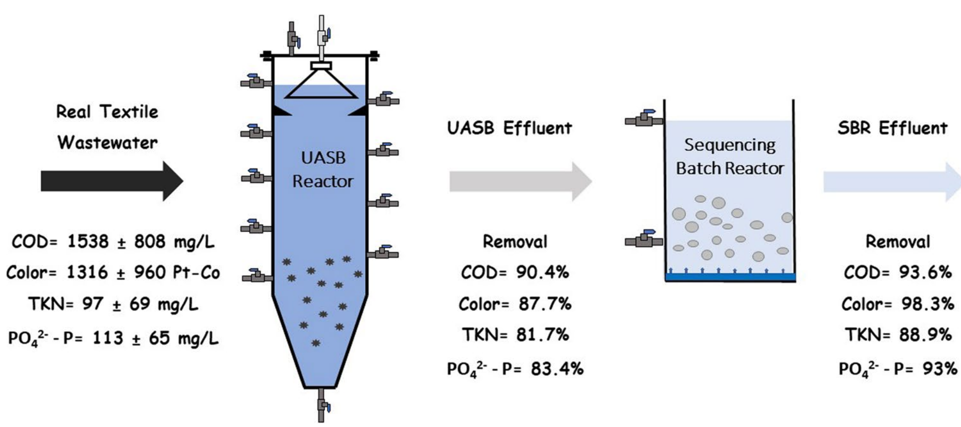
Received: 10 August 2021 / Revised: 14 November 2021 / Accepted: 22 November 2021 / Published online: 7 January 2022

Abstract

A hybrid anaerobic–aerobic treatability of real textile wastewater was investigated by using a lab-scale upflow anaerobic sludge blanket (UASB) coupled with a sequencing batch reactor (SBR). The performance of the integrated system was determined under various operational conditions. In phase I of the study, the UASB reactor was operated and optimized on real textile wastewater. The UASB was operated at a hydraulic retention time of 48 h in a semi-continuous mode with 12-h feeding and 12-h non-feeding cycle. Volatile fatty acid to alkalinity ratio was kept in the range of 0.42–0.72, while pH was strictly maintained between 6.8 and 7.2 under mesophilic conditions (35 °C). In phase II of the study, SBR was coupled with a UASB reactor and operated on real textile wastewater. The SBR was operated at an HRT of 6 h and solids retention time of 20 days. The integrated system was optimized with maximum removal efficiencies of 98% for chemical oxygen demand, 94% for color, 93% for total Kjeldahl nitrogen, and 89% for orthophosphate phosphorus. The results indicated that the integrated system is robust and flexible for the treatment of textile wastewater.

Graphical abstract



Keywords Feeding and non-feeding cycle · Hybrid treatment · Organic loading rate · Organic removal · Semi-continuous mode

Editorial responsibilty: Senthil Kumar Ponnusamy.

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Introduction

The textile industry is currently at a boom as compared to other renowned industrial sectors of Pakistan. Pakistan is the 8th largest exporter of textile products among Asian countries. This sector contributes 52% of the country's total exports (USD 12.36 Billion) having a share of 8.5% in total Gross Domestic Product (GDP) and providing employment to 40% people of the country (Rongrong et al. 2011). The continuous advancement of the textile industry to fulfill the global textile requirement is disturbing the environment in several ways. Pollution of water bodies due to untreated textile wastewater is considered as one of the foremost environmental concerns (Verma et al. 2016).

Globally, the textile industry has one of the most complex and longest industrial process chains in the manufacturing sector. Dyeing and finishing units of a textile industry use large volumes of water and considerable quantities of complex chemicals including dyes. Water consumption for 1 kg of textile product is approximately 200 L (Ghaly et al. 2014). The wastewater generated by several textile processing units is categorized as one of the most polluted wastewaters of various industrial sectors with regard to its composition (Chequer et al. 2013; Haddad et al. 2018). It is generally characterized by fluctuating high values of pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), strong color and low biodegradability of recalcitrant compounds (Sathya et al. 2019; Kaur et al. 2019).

Almost all the physicochemical and biological treatment methods have been investigated for the treatment of textile wastewater. Several technologies have been developed and used in the recent past for the treatment of textile wastewater, e.g., advanced oxidation process, chemical coagulation method, activated sludge process, etc. However, no particular method has emerged as a panacea due to high operational costs, more sludge production and compromised treatment efficiency (Collivignarelli et al. 2019). The biological treatment methods are preferred worldwide for textile wastewater treatment (Shaul et al. 1991; Hai et al. 2007; Belli et al. 2019). Low operating costs and reduced environmental impacts are some of the benefits of biological systems. Biological treatment involves the bio-transformation of contaminants for energy generation, release of carbon and other essential minerals to sustain the microbial culture (Punzi 2015). It merely eliminates the soluble matter present in the textile effluent. The ratio of organic loading to the concentration of dyes present and microbial population, the temperature of the treatment system and the available concentration of dissolved oxygen (DO) influence the removal efficiency (Holkar et al. 2016).

Biological treatment systems can be classified based on the oxygen requirement of the microorganisms. They include the aerobic, anaerobic, anoxic or facultative and/or amalgamation of these systems (Holkar et al. 2016). Various aerobic biological methods including the activated sludge process with its different attached and suspended modifications have been reported and used. However, the recalcitrant compounds and azo dyes present in textile wastewater are very resilient to biological degradation in aerobic environments. The aerobic bacteria are incapable of degrading the complex dye molecules; hence, the effluent generated may be low in organics but highly colored (Yasar and Tabinda 2010). Therefore, anaerobic treatment can be used as an alternative and advantageous technique to treat textile wastewater (Hai et al. 2007). Anaerobic treatment methods are effective in treating textile wastewaters, especially for decolorization (Firmino et al. 2010; Spagni et al. 2012). Anaerobic processes result in high color removal efficiency by reducing azo bonds. They are preferred over aerobic processes due to their capability to absorb organic shocks and higher organic loads, less energy requirements and low sludge generation (Punzi 2015; Castro et al. 2020).

Although anaerobic processes are consistent in organics and color removal, high COD and bacteriological concentration in the effluent are the limitations of this technology. In order to conform with the new environmental regulations and discharge standards (Ahmadi et al. 2015) and high effluent quality for reuse potential, integrated anaerobic–aerobic treatment systems are generally considered to be viable (Buntner et al. 2013; Yan et al. 2013; Yen et al. 2016). In the combined treatment, anaerobic microbes cleave the azo bond and also reduce the high organic load while aerobic post-treatment removes the dye by products and further reduces the organic load to the acceptable level (Saratale et al. 2011; Paździor et al. 2017). Few studies have been found in the literature containing the combined anaerobic–aerobic treatment of textile wastewater (O'neill et al. 2000a; b; Kalyuzhnyi and Sklyar 2000; Shaw et al. 2002; Sponza and Işik 2002; Melgoza et al. 2004; Işık and Sponza 2008). The majority of these studies are on the treatment of synthetic textile wastewater, and very few studies have been found in the literature for the treatment of real textile wastewater.

To tackle the textile wastewater related issues and especially the color removal, various anaerobic treatment processes have been investigated for the last few decades (Wang et al. 2011; Jing et al. 2013). Among the multitudinous treatment options, upflow anaerobic sludge blanket reactor (UASB) is one of the most extensively used anaerobic treatment technologies to treat versatile wastewaters including textile wastewater (Lu et al. 2015). UASB is a type of reactor in which the influent wastewater is fed from the bottom of the reactor. The introduced wastewater flows upward having a continuous contact with the sludge bed (Calero et al. 2018; Callejas et al. 2019), which leads to the stabilization of organic matter and dye removal. The formation of dense and thick sludge bed in UASB is one of the decisive factors in better removal efficiencies of organic load and color. This sludge bed is formed and gets denser with the passage of time due to inflowing suspended solids and an increase in the microbial population. The granules (sludge bed) have very good settling properties and are not vulnerable to the sludge washout from the system (Buntner 2013; Mousavian et al. 2019). In aerobic processes, sequencing batch reactors (SBRs) have displayed an improved treatment performance efficiency with ease of operation. The system is established by employing high mixed liquor suspended solids (MLSS) concentration with the provision of airflow for biodegradation. Furthermore, SBR combines all the processes in a single reactor or tank resulting in a compact system and operational ease (Calero et al. 2018). Therefore, the application of SBR as a post-treatment to UASB can help achieve high-quality treated water that may comply with new international standards paving a way towards wastewater reuse and sustainability in the textile industry.

The aim of this research was to evaluate the performance and applicability of anaerobic–aerobic integrated system and its optimization in terms of COD, color, orthophosphate phosphorus (PO_4^{3-}–P) and total Kjeldahl nitrogen (TKN) removal. The treatability study was carried out on real textile wastewater in Water and Wastewater Laboratory of Institute of Environmental Sciences and Engineering (IESE), National University of Sciences and Technology, Islamabad, Pakistan, from March 2018 to April 2019. This study explored the potential of the anaerobic treatment process for the pre-treatment of extremely contaminated and recalcitrant textile wastewater which still poses a big challenge to the stakeholders for efficient treatment. The anaerobic treatment was followed by aerobic SBR as polishing treatment to meet stringent international effluent standards and to comply with the demands of Zero Discharge of Hazardous Chemicals (ZDHC) initiative (Ahmadi et al. 2015).

Materials and methods

Experimental setup of UASB reactor

A bench scale UASB reactor was installed and operated in the Water and Wastewater Laboratory, NUST, Islamabad. The reactor was made up of transparent acrylic material having a working volume of 10.8 L with an internal diameter and height of 127 and 850 mm, respectively, as shown in Fig. 1. The reactor was also provided with a gas–liquid-solid separator to separate biogas from the anaerobic sludge and the liquid effluent. The influent was fed from the bottom of the reactor, while effluent was recovered from the top of the reactor. A small volume of the effluent at a flow rate of 120 ml/min was recirculated in the system to degrade the recalcitrant compounds as well as to maintain the desired up-flow velocity of 0.5 m/hr. Influent and effluent flow rates were controlled by variable velocity peristaltic pumps (Masterflex—L/S Easy Load II EW-77200–62, US). Digital timers (OMRON-DH48S-S, Japan) were employed to regulate the operational cycle. The temperature was maintained at 35 °C throughout the study by a Digital ON/OFF Temperature Control Device (Emko Electronik-ESM-3710-N, Turkey) connected with a magnetic contactor (LG-MEC GMC-12, South Korea). A manual mixer was also provided in the reactor for better mixing and interaction of biomass with the substrate once a day. It was also used prior to sample collection for MLSS analysis.

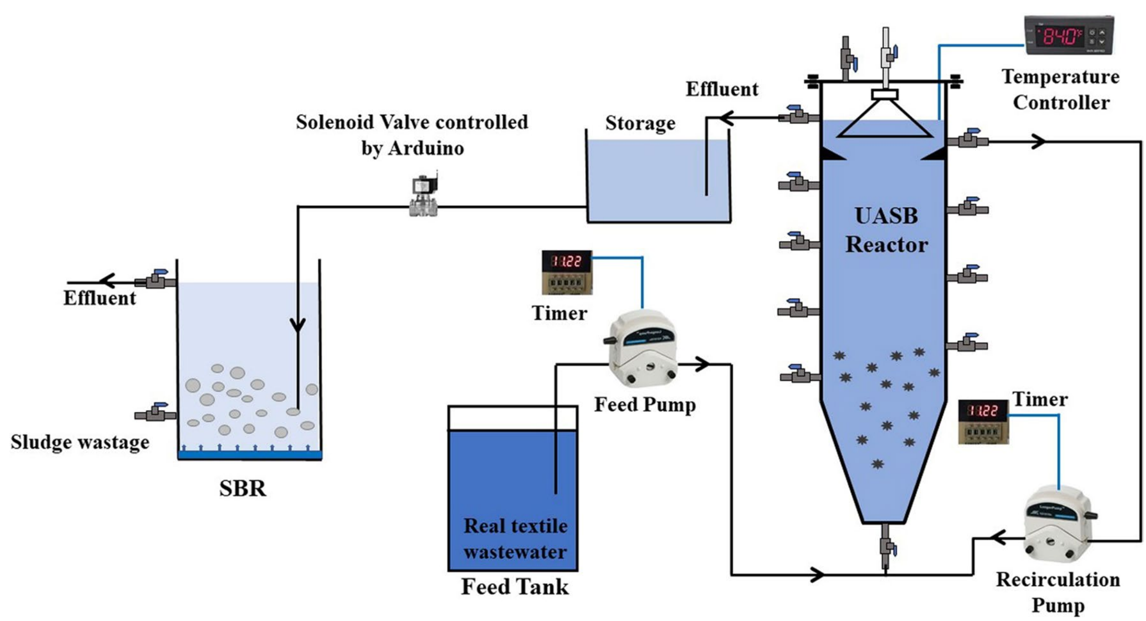

Fig. 1 Schematic diagram of laboratory-scale hybrid UASB-SBR system

Experimental setup of SBR

The aerobic SBR was operated using the anaerobic effluent of UASB. The reactor was circular with 127 mm diameter and 680 mm height, having an effective volume of 8.6 L as shown in Fig. 1. The aeration was provided with the air pump (HAILEA V-10) having a flow rate of 10 L/min to maintain an aerobic environment for microbial growth, biomass suspension, organic degradation and to create turbulence in order to avoid dead zone formation at the bottom of the reactor. The system was provided with the programmable logic controller (PLC) having an Arduino Uno microcontroller and ON/OFF timers to automate the cycle completely. The Arduino Uno microcontroller was programmed by using open-source Arduino software Integrated Development Environment (IDE) 1.0.6. Anaerobically treated wastewater was subsequently introduced to the aerobic SBR via an automatically controlled solenoid valve (Sizto Tech Corporation-2W010-040 Series, US).

Reactor operation

Figure 1 shows a flow diagram of a laboratory-scale integrated UASB-SBR system. Real textile wastewater, generated as a result of various processes of a vertically integrated textile setup, was obtained from a privately managed textile industry located in Rawalpindi, Pakistan. The homogenized samples were collected on weekly basis by using 24-h composite sampling method and were preserved at 4 ºC until used for experimental study.

The wastewater was highly variable in its characteristics, however; typical values of various parameters are listed in Table 1. The pH of the influent wastewater was adjusted to the neutral range (6.8–7.2) by adding 0.4 N hydrochloric acid (HCl) before feeding to the UASB reactor.

Table 1 Typical characteristics of real textile wastewater

Parameter	Unit	Value
pH	–	10.5 ± 2
Temperature	°C	45 ± 5
Chemical oxygen demand (COD)	mg/L	1538 ± 808
Biochemical oxygen demand (BOD)	mg/L	370 ± 170
Total dissolved solids (TDS)	mg/L	2350 ± 150
Total suspended solids (TSS)	mg/L	550 ± 100
Color	Pt–Co	1316 ± 960
Total Kjeldahl Nitrogen (TKN)	mg/L	97 ± 69
Orthophosphate phosphorus (PO_4^{3-}-P)	mg/L	113 ± 65

Start-up phase of UASB

Anaerobic sludge was obtained from a UASB reactor previously operated on synthetic textile wastewater (Haider et al. 2018). The sludge was acclimatized to real textile wastewater for 110 days before analyzing the performance of the biological treatment system. The supernatant was removed on every alternate day, i.e., after 48 h, being hydraulic retention time (HRT) of anaerobic treatment system; by siphoning it off to avoid sludge washout from the reactor. Real textile wastewater was added as a feed for the batch system after the decanting process. To enhance the sludge granulation, 0.4 L of cow dung slurry was inoculated into the batch reactor and was run until the sludge color changed to dark black with distinctive odor and maximum bubbles formation indicating the production of biogas. The operational conditions kept during the start-up phase of the UASB reactor are reported in Table 2.

Semi-continuous operation of UASB

The UASB reactor was filled with one-third (i.e., 3.6 L) of the reactor's working volume with anaerobically acclimatized sludge. The MLSS concentration was 6000–7700 mg/L with volatile suspended solids-to-total suspended solids ratio (VSS/TSS) of 0.67. The desired alkalinity was maintained in the reactor by supplementing with 0.1 N sodium hydrogen carbonate ($NaHCO_3$).

The UASB reactor was operated at HRT of 48 h in a semi-continuous mode with 12-h feeding, 12-h non-feeding, again 12-h feeding and 12-h non-feeding cycles. The effluent was recycled through an effluent recirculation port

Table 2 Operational conditions during various phases of operation

Phase	Run time (Days)	Duration (Days)	No. of runs	HRT (h)		OLR (kg COD/m^3/day)		SRT (Days)	
				UASB	SBR	UASB	SBR	UASB	SBR
Start-up phase of UASB (batch)	0–110	110	–	48	–	0.74 ± 0.3	–	Infinite	–
Semi-continuous operation of UASB (stand-alone treatment)	110–202	92	–	48	–	0.74 ± 0.3	–	Infinite	–
Semi-continuous operation of UASB-SBR (integrated setup)	202–246	44	5	48	6	0.8 ± 0.2	0.4 ± 0.2	Infinite	20
	246–268	22	4	48	6	0.7 ± 0.3	0.2 ± 0.1	Infinite	20
	268–332	64	7	48	6	0.9 ± 0.2	0.1 ± 0.06	Infinite	20

to maintain the desired upflow velocity of 0.5 m/hr and to keep the anaerobic biomass in suspension for better COD removal efficiency. HRT of 48 h was chosen on the basis of previous studies in treating synthetic textile wastewater (Lawrence and McCarty 1970; Buitrón and Carvajal 2010; López-López et al. 2015).

Semi-continuous operation of UASB and SBR

From day 202 onward, the aerobic sequencing batch reactor (SBR) was employed to enhance the quality of anaerobically treated wastewater from UASB. The SBR was operated in 5 sub-cycles including react, settle, decant and idle starting with feeding of anaerobically pre-treated wastewater as an influent (Gu et al. 2017). The operation of integrated UASB-SBR was divided into three phases based on average organic loading rate (OLR) corresponding to removal efficiencies of COD, color, TKN and PO_4^{3-}-P. The three phases of the integrated system and their associated number of runs and days are shown in Table 2.

The sequencing batch reactor was subjected to operation under ambient temperature. The MLSS concentration and the ratio of mixed liquor volatile suspended solids to mixed liquor suspended solids (MLVSS/MLSS) were in the range of 6000–7000 mg/L and 0.6–0.7, respectively. Airflow was introduced at a rate of 10 L/min to maintain the DO concentration above 2 mg/L. The reactor was operated at an HRT of 6 h throughout the study period. The solids retention time (SRT) for UASB was fixed to be infinite, whereas, in the case of aerobic SBR, the SRT was maintained at 20 days. This was performed by wasting 430 mL of mixed liquor from the reactor daily. The integrated system was operated for more than 100 days after complete optimization of the whole system was achieved in terms of COD, color, TKN and PO_4^{3-}–P removals.

Treatment performance parameters including COD, color, TKN and PO_4^{3-}-P removals were analyzed after 48 h and operational parameters including volatile fatty acid (VFA), alkalinity, MLSS, MLVSS and DO were analyzed on daily basis. The stability and optimal working of reactor were determined by these parameters (Von Sperling and de Lemos Chernicharo 2017).

Analytical methods

The conventional physicochemical parameters were determined as described in Standard Methods (APHA 2018). For the UASB reactor, samples were collected from the sampling port located 65 mm below the effluent port in non-feeding phase of the reactor, whereas for sequencing batch reactor, the sample was collected in the idle phase. The supernatant was collected and taken for analysis of different parameters. Temperature, pH, alkalinity, TKN, PO_4^{3-}–P, total suspended solids (TSS), volatile suspended solids (VSS), color and soluble COD were analyzed. For measurement of soluble COD, color and PO_4^{3-}-P, samples were passed through a 0.45-μm filter paper prior to analysis.

Statistical analysis

To validate the effects of operational conditions on COD, color, TKN and PO_4^{3-}-P removals, one-way analysis of variance (ANOVA) was used. The statistical variations were studied with a confidence level of 95% as an impact of intermittent operation and varying OLRs during the operation of the integrated setup.

Results and discussion

Start-up phase of UASB reactor

The start-up period of the UASB reactor was completed in 110 days. Initially, the MLSS concentration in the anaerobic reactor was 2300 mg/L at the beginning of this phase. The COD removal efficiency was determined and was relatively poor at the beginning as the microbial population was incapable of degrading the organic matter present in the textile effluent. However, the MLSS concentration and MLVSS/MLSS ratio started to rise with time, representing an increase in the active biomass resulting in better organic and color removal (Sathya et al. 2019). This may also relate to an effective start-up of the UASB reactor.

Semi-continuous operation of UASB reactor

The anaerobic sludge being acclimatized during the start-up phase was then subjected to the semi-continuous operation of UASB. At the start, the removal efficiencies of COD, color, TKN and PO_4^{3-}-P were extremely poor as the sludge was introduced to modified operating conditions in contrast to the start-up phase. During the first 28 days of UASB operation, the removal efficiencies of COD and color were below 30 and 15%, respectively, at an average OLR of 0.8 ± 0.3 kg COD/m^3/day. This resulted in poor effluent quality due to high organic load and the trend continued until the anaerobic sludge got acclimated to the variable organic and color load. The removal efficiency gradually improved and increased above 80 and 55% for COD and color, respectively, on day 92 of UASB operation, with an average OLR of 0.74 ± 0.3 kg COD/m^3/day. From this point onwards, anaerobic effluent was subjected to aerobic SBR for further polishing.

Semi-continuous operation of Integrated UASB-SBR system

Effect of organic loading rate

Due to fluctuating influent COD concentrations, the organic loading rate (OLR) also remained inconstant throughout the study. During the first 5 runs of integrated system operation, the influent OLR was 0.8 ± 0.2 kg COD/m^3/day. It was reduced to 0.7 ± 0.3 kg COD/m^3/day for the next 4 runs as the anaerobic reactor prior to the SBR improved the removal efficiency, leading to low COD concentration in the effluent and ultimately lower OLR for the subsequent SBR setup. However, for the last 7 runs, again the OLR raised to 0.9 ± 0.2 kg COD/m^3/day due to increased COD load to the UASB reactor, but it did not affect the removal efficiency as the microbial communities became adapted to the variable OLRs.

Effluent pH

Effluent pH value is an indicator of stable reactor operation besides VFA/alkalinity ratio. The pH of the effluent during first 5 runs, with an average OLR of 0.8 ± 0.2 kg COD/m^3/day, was in a range of 6.77 ± 0.08. However, it fluctuated till it became stabilized up to a value of 6.60 ± 1.23 after 268 days of the study. This is due to the fact that the influent pH did not change despite addition of HCl due to the presence of high alkalinity which resists change in pH. In the last 7 runs, the reactor achieved stability as the pH was within the neutral range of 7.06 ± 0.35 till the end of the study day from 325 to 332.

VFA/alkalinity ratio

VFA/alkalinity ratio exhibited a trend relative to the effluent pH. During the first 5 runs of integrated system operation, it remained inconsistent as the sludge was getting acclimatized to hydraulic and organic loads. An average VFA/alkalinity ratio of 0.52 ± 0.06 was found with an average organic loading rate of 0.8 ± 0.2 kg COD/m^3/day. VFA/alkalinity ratio must be below 0.4 for a stable operation of UASB (Zhang et al. 1995). But in this study, it was established that the reactor worked better and efficiently when VFA/alkalinity ratio was in the range of 0.34–0.53. The ratio was further reduced to 0.34 ± 0.03 on 268 days of operation. The reactor was optimized with an average ratio of 0.53 during the study, and it maintained the ratio of 0.34 ± 0.02 as the system moved to the steady-state condition with no further fluctuations in VFA/alkalinity ratio.

Chemical oxygen demand and color removal efficiencies

COD and color removal were the two most important parameters of this study. UASB showed very encouraging results in terms of COD and color removal with improvement in the performance of the integrated system. Results revealed that both color and COD removal efficiencies were low at lower HRT values. The differences of COD and color removals were found to be significant by one-way ANOVA ($P < 0.05$) during the operation of integrated setup as exhibited in Table 3. During the acclimatization phase of semi-continuous operation of UASB and SBR with an average OLR of 0.8 ± 0.2 kg COD/m^3/day, COD removal efficiency remained below 90% till the end of the 4th run (up to first 34 days of operation of the integrated system) (Fig. 2). This may be related to the toxicity of textile wastewater, the presence of recalcitrant compounds and excess wash out of suspended biomass flowing out with the effluent which was again introduced and the MLSS concentration became stabilized. Furthermore, rapid escalation of organic loads resulted in delayed acclimatization of sludge to real conditions of the integrated system. The system achieved the removal efficiency of 92% at the end of the 5th run (44 days of integrated system operation).

The COD removal efficiency was observed to improve gradually due to acclimatization of anaerobic biomass to the fluctuating organic and hydraulic loads. With the passage of time, the pH value dropped down the neutral range and resulted in steady-state conditions within the reactors. The COD removal increased to 97% at the end of the 9th

Table 3 ANOVA for COD, color, TKN and orthophosphate phosphorous removal during UASB and coupled UASB-SBR operation

Phase	Parameters	F	P-value
UASB rector (as stand-alone treatment)	COD removal	54.5	< 0.001
	Color removal	49.8	< 0.001
	TKN removal	22.7	< 0.001
	PO_4^{3-}-P removal	39.4	< 0.001
UASB reactor coupled with SBR (integrated setup)	COD removal	41.5	< 0.001
	Color removal	71.6	< 0.001
	TKN removal	67.5	< 0.001
	PO_4^{3-}-P removal	78.0	< 0.001

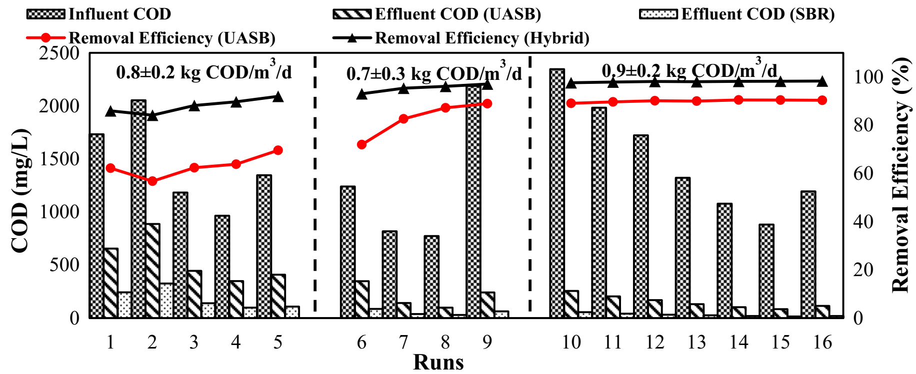

Fig. 2 Variation of COD removal during various organic loading rates of integrated UASB-SBR operation

run (66 days of integrated system operation) at an average OLR of 0.7 ± 0.3 kg COD/m³/day, with pH and VFA/alkalinity values in the desired neutral range and below 0.4, respectively. During the last 7 runs at an average OLR of 0.9 ± 0.2 kg COD/m³/day, the system showed steady-state characteristics with no drastic fluctuations in the performance. The operational parameters including pH and VFA/alkalinity ratio were in the optimized range for effective working of the anaerobic reactor. Moreover, the system became mature and acclimatized to the variations of the influent wastewater and maximum removal efficiency of 98% for COD was achieved at the end of the 16th run (130 days of integrated system operation).

The progressive change in the COD removal in the integrated system with time is in accordance with the study carried out previously (Punzi 2015), which reports several factors responsible for improving the removal efficiency. The presence of carbon source in the form of starch rather than glucose may have contributed to the better removal efficiency of COD. This is due to the fact that starch is a more intricate source of carbon as compared to glucose. In the textile industry, starch is extensively used in singeing for strengthening of the fibers (Schönberger and Schäfer 2003). The greater concentration of starch and sodium chloride used in the processing of fabric (Schönberger and Schäfer 2003) may have exerted selective pressure on the microbial population (Punzi 2015). Acclimatization of these communities to the adverse conditions and fluctuating characteristics of the wastewater enhanced their performance with regard to starch metabolism and COD removal. The variation of influent and effluent COD in addition to removal efficiency is shown in Fig. 2.

The effect of color removal at 54 h HRT (48 h UASB and 6 h SBR) is shown in Fig. 3. Literature suggests that although color removal efficiency is not considerably affected by HRT, 48-h HRT of UASB reactor was appropriate to optimize other performance parameters as well. It is evident from Fig. 3 that the removal efficiency of the integrated system was below 70% at the end of the 4th run (till day 32) with an average OLR of 0.8 ± 0.2 kg COD/m³/day, as the microbial culture was becoming adapted to the fluctuating influent characteristics. But as the sludge became acclimatized to the toxic dyes in the influent, actual reductive cleavage of azo bonds occurred. The absolute decomposition of azo bonds in a strictly reductive environment occurs by the electrons present in the carbon sources of wastewater (Zhang et al. 1995). In this study, we cannot relate color removal efficiency to this reason as the BOD/COD ratio remained less than 0.3 for most of the time. The only possible reason for better removal efficiency is the sludge and microbial consortium acclimatization to the azo bonds (Haddad et al. 2018). For optimized state achieved for this

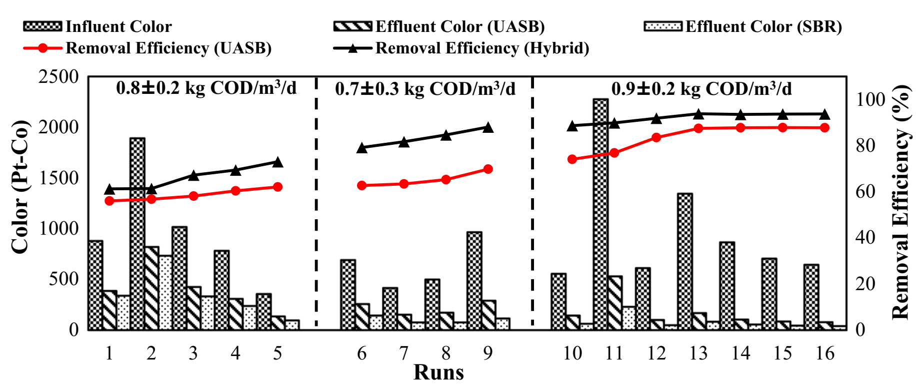

Fig. 3 Variation of color removal during various organic loading rates of integrated UASB-SBR operation

study, color removal of 93% was considered an optimum color removal during the 13th run (on day 104 of integrated system operation) at an average OLR of 0.9 ± 0.2 kg COD/m^3/day, with other parameters also at steady-state and no significant changes in the removal efficiencies.

Total Kjeldahl nitrogen removal efficiency

Ammonium nitrogen (NH_4^+-N) and organic nitrogen collectively form total Kjeldahl nitrogen (TKN). The differences of TKN removals were statistically significant ($P < 0.05$) during all phases of integrated system operation (Table 3). The variation of TKN removal through integrated UASB-SBR treating real textile wastewater is depicted in Fig. 4. The TKN removal efficiency of combined UASB and SBR at an average OLR of 0.8 ± 0.2 kg COD/m^3/day was below 70% till the 5th run (on day 38 of the integrated system operation) (Fig. 4). This is due to the fact that the biomass of aerobic SBR was acclimating with the real conditions of the reactor. The nitrification process can be completed in aerobic sequencing batch reactor at low organic loads and feasible environmental conditions (Ji et al. 2015). Nitrifying bacteria are considered as slow-growing microorganisms (Velasco-Garduño et al. 2019). The fundamental condition for the nitrification process to occur is that the growth rate of nitrifiers including ammonium-oxidizing bacteria (AOBs) and nitrite-oxidizing bacteria (NOBs) is faster than the net rate of biomass withdrawal of biomass from the aerobic SBR. Therefore, SRT of 20 days was sustained in order to keep the MLSS concentration within a range of 6000–7000 mg/L to attain maximum nitrification in SBR setup.

The maximum removal efficiency of TKN was found in aerobic sequencing batch reactor operating at 6 h HRT along with the maximum removal efficiencies of color and COD. Previous studies have reported that nitrogen concentration is required by microbial population in activated sludge process as nutrition for the growth of biomass (Zhidong et al. 2009). In addition to this requirement, the maximum TKN removal efficiency of the integrated system was optimized with an average OLR of 0.9 ± 0.2 kg COD/m^3/day from the 12th run to the end of the research study with total removal efficiency over 93% with no further variations (Fig. 4). Total nitrogen was removed in a two-step process: firstly, by biotransformation of organic nitrogen into ammonium nitrogen (NH_4^+-N) and then by the aerobic conversion of ammonium nitrogen (NH_4^+-N) to nitrite (NO_2^-) and then eventually to nitrate (NO_3^-).

Orthophosphate phosphorus removal efficiency

One of the most commonly used and viable methods for phosphorus removal from wastewaters is enhanced biological phosphorus removal (EBPR). This process involves the operation of a conventional activated sludge process with anaerobic–aerobic conditions to enhance and stimulate the growth of phosphorus accumulating organisms (PAOs) (Oehmen et al. 2005). During anaerobic treatment, PAOs uptake the volatile fatty acids (VFAs) and transform them into poly-b-hydroxyalkonates (PHAs) (Mino et al. 1998; Oehmen et al. 2005). UASB reactor is considered to be inefficient in phosphorus removal. The possible reason could be the low BOD-to-COD ratio of the influent (Asadi et al. 2012). However, the PO_4^{3-}-P removal in the UASB reactor during this study was in contrast to the results reported in the literature, with removal efficiency as 82% at steady-state conditions. This could probably be due to the fact that the phosphate release may have occurred in forms other than soluble orthophosphate phosphorus (Melcer 2004). The reported phosphorus removal efficiencies in the literature

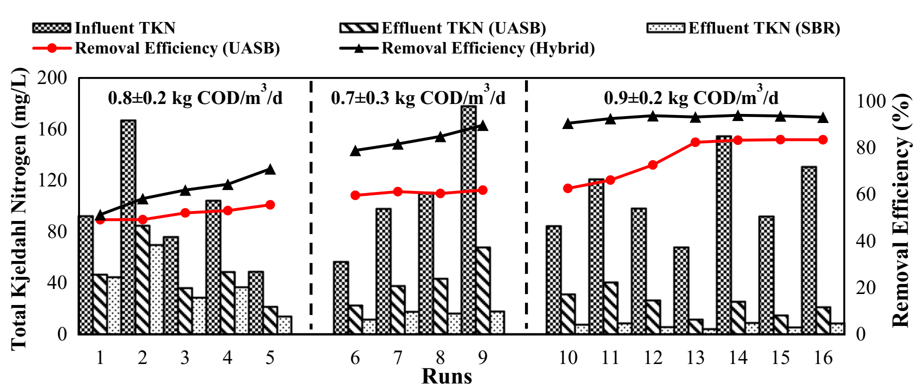

Fig. 4 Variation of TKN removal during various organic loading rates of integrated UASB-SBR operation

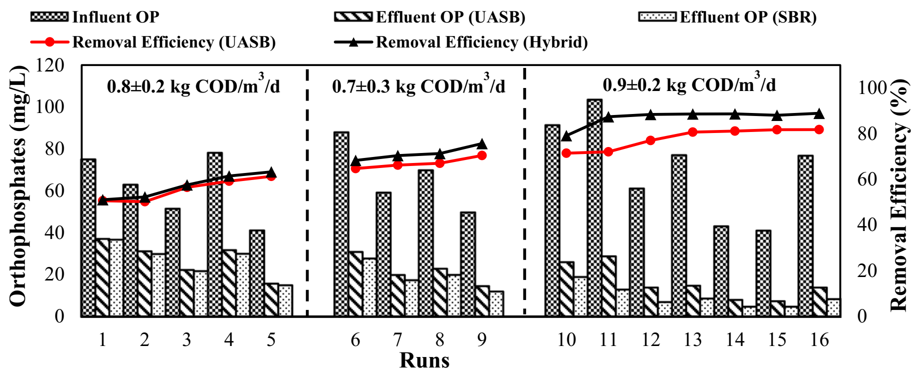

Fig. 5 Variation of orthophosphate phosphorus removal during various organic loading rates of integrated UASB-SBR operation

are for total phosphorus which not only includes the organic phosphates but also the soluble and particulate orthophosphate phosphorus. Organic phosphates are any phosphates contained inside or bonded to an organic compound. In the same sample, total phosphorus concentrations will always be larger than the orthophosphate phosphorus concentration.

However, under aerobic environment, the PHAs are oxidized by phosphorus-accumulating organisms (PAOs) resulting in energy generation for growth, glycogen replenishment and phosphorus uptake. During the operation of aerobic SBR subsequent to the anaerobic UASB, the PO_4^{3-}-P removal efficiency was below 65% at the end of the 5th run with an average OLR value of 0.8 ± 0.2 kg COD/m^3/day. This removal efficiency was achieved in the aerobic SBR through the excess sludge wasted with enriched orthophosphate phosphorus content (Oehmen et al. 2005). The efficiency of the integrated UASB-SBR system for PO_4^{3-}-P removal efficiency was just above 88% at an average OLR of 0.9 ± 0.2 kg COD/m^3/day, and it remained consistent with no further variation till the end of the 17th run (near day 120 to 130). Analysis of variance (ANOVA) showed that the differences in removal efficiency of PO_4^{3-}-P are significant ($P < 0.05$) as depicted in Table 3. The overall variation of orthophosphate phosphorus removal through integrated UASB-SBR treating real textile wastewater is depicted in Fig. 5.

Conclusion

This experimental research successfully achieved its objectives by optimization of integrated UASB-SBR system treating real textile wastewater with fluctuations in its organic as well as physicochemical parameters. The integrated system was optimized with maximum removal efficiencies of 98% for COD, 94% for color, 93% for total Kjeldahl nitrogen (TKN) and 89% for orthophosphate phosphorus (PO_4^{3-}-P). It is pertinent to infer that aerobic SBR facilitated the entire treatment process and paved the way for the possible reclamation and reuse of treated wastewater. This may also lead to compliance with the zero discharge of hazardous chemicals (ZDHC) initiative for the textile industries which was intended to be achieved by 2020. Therefore, the current research concludes that the integrated anaerobic–aerobic system is capable of treating extremely recalcitrant real textile wastewater resulting in sustainable development and reduced pollution stress on natural water resources.

Acknowledgements The authors would like to acknowledge the financial support provided for this study by MS Research Grant by National University of Sciences and Technology (NUST), Islamabad, Pakistan.

Authors' contributions M.U.S was involved in conceptualization, experimental work & analysis and writing-original draft. S.J.K was involved in writing-review and editing and supervision. H.M.A.S was involved in support in experimental work and analysis. Z was involved in writing, review and editing.

Funding Financial support for this research was provided by National University of Sciences and Technology (NUST), Islamabad, Pakistan.

Declarations

Conflicts of interest The authors have no conflicts of interest related to this paper.

References

Ahmadi E, Gholami M, Farzadkia M, Nabizadeh R, Azari A (2015) Study of moving bed biofilm reactor in diethyl phthalate and diallyl phthalate removal from synthetic wastewater. Bioresource Technol 183:129–135

APHA (2018) Standard methods for the examination of water and wastewater, APHA, AWWA, WEF, Washington, DC

Asadi A, Zinatizadeh A, Sumathi S (2012) Simultaneous removal of carbon and nutrients from an industrial estate wastewater in a single up-flow aerobic/anoxic sludge bed (UAASB) bioreactor. Water Res 46(15):4587–4598

Belli T, Battistelli A, Costa R, Vidal C, Schlegel A, Lapolli F (2019) Evaluating the performance and membrane fouling of an electro-membrane bioreactor treating textile industrial wastewater. Int J Environ Sci Technol 16(11):6817–6826

Buitrón G, Carvajal C (2010) Biohydrogen production from Tequila vinasses in an anaerobic sequencing batch reactor: effect of initial substrate concentration, temperature and hydraulic retention time. Bioresource Technol 101(23):9071–9077

Buntner D (2013) Combined UASB-MBR system for the treatment of low-strength wastewater at ambient temperatures, Universidade de Santiago de Compostela

Buntner D, Sánchez A, Garrido J (2013) Feasibility of combined UASB and MBR system in dairy wastewater treatment at ambient temperatures. Chem Eng J 230:475–481

Calero R, Iglesias-Iglesias R, Kennes C, Veiga M (2018) Organic loading rate effect on the acidogenesis of cheese whey: a comparison between UASB and SBR reactors. Environ Technol 39(23):3046–3054

Callejas C, Fernández A, Passeggi M, Wenzel J, Bovio P, Borzacconi L, Etchebehere C (2019) Microbiota adaptation after an alkaline pH perturbation in a full-scale UASB anaerobic reactor treating dairy wastewater. Bioproc Biosyst Eng 42(12):2035–2046

Castro F, Bassin J, Alves T, Sant'Anna G and Dezotti M, (2020) Reactive Orange 16 dye degradation in anaerobic and aerobic MBBR coupled with ozonation: Addressing pathways and performance. Int J Environ Sci Technol 1:1–20

Chequer FMD, de Oliveira GAR, Ferraz ERA, Cardoso JC, Zanoni MVB and de Oliveira DP (2013) Eco-friendly textile dyeing and finishing. InTech

Collivignarelli MC, Abbà A, Miino MC, Damiani S (2019) Treatments for color removal from wastewater: State of the art. J Environ Manag 236:727–745

Firmino PIM, da Silva MER, Cervantes FJ, dos Santos AB (2010) Colour removal of dyes from synthetic and real textile wastewaters in one-and two-stage anaerobic systems. Bioresource Technol 101(20):7773–7779

Ghaly A, Ananthashankar R, Alhattab M, Ramakrishnan V (2014) Production, characterization and treatment of textile effluents: a critical review. J Chem Eng Process Technol 5(1):1–18

Gu J, Xu G, Liu Y (2017) An integrated AMBBR and IFAS-SBR process for municipal wastewater treatment towards enhanced energy recovery, reduced energy consumption and sludge production. Water Res 110:262–269

Haddad M, Abid S, Hamdi M, Bouallagui H (2018) Reduction of adsorbed dyes content in the discharged sludge coming from an industrial textile wastewater treatment plant using aerobic activated sludge process. J Environ Manag 223:936–946

Hai FI, Yamamoto K, Fukushi K (2007) Hybrid treatment systems for dye wastewater. Crit Rev Env Sci Technol 37(4):315–377

Haider A, Khan SJ, Nawaz MS, Saleem MU (2018) Effect of intermittent operation of lab-scale upflow anaerobic sludge blanket (UASB) reactor on textile wastewater treatment. Desalin Water Treatment 136:120–130

Holkar CR, Jadhav AJ, Pinjari DV, Mahamuni NM, Pandit AB (2016) A critical review on textile wastewater treatments: possible approaches. J Environ Manag 182:351–366

Işık M, Sponza DT (2008) Anaerobic/aerobic treatment of a simulated textile wastewater. Sep Purif Technol 60(1):64–72

Ji B, Yang K, Zhu L, Jiang Y, Wang H, Zhou J, Zhang HJB, Engineering B (2015) Aerobic denitrification: a review of important advances of the last 30 years. Biotechnol Bioprocess Eng 20(4):643–651

Jing Z, Hu Y, Niu Q, Liu Y, Li Y-Y, Wang XC (2013) UASB performance and electron competition between methane-producing archaea and sulfate-reducing bacteria in treating sulfate-rich wastewater containing ethanol and acetate. Bioresource Technol 137:349–357

Kalyuzhnyi S, Sklyar V (2000) Biomineralisation of azo dyes and their breakdown products in anaerobic-aerobic hybrid and UASB reactors. Water Sci Technol 41(12):23–30

Kaur P, Sangal V, Kushwaha J (2019) Parametric study of electro-Fenton treatment for real textile wastewater, disposal study and its cost analysis. Int J Environ Sci Te 16(2):801–810

Lawrence AW, McCarty PL (1970) Unified basis for biological treatment design and operation. J Sanit Eng Div Asce 96(3):757–778

López-López A, León-Becerril E, Rosales-Contreras ME, Villegas-García E (2015) Influence of alkalinity and VFAs on the performance of an UASB reactor with recirculation for the treatment of Tequila vinasses. Environ Technol 36(19):2468–2476

Lu X, Zhen G, Estrada AL, Chen M, Ni J, Hojo T, Kubota K, Li Y-Y (2015) Operation performance and granule characterization of upflow anaerobic sludge blanket (UASB) reactor treating wastewater with starch as the sole carbon source. Bioresource Technol 180:264–273

Melcer H (2004) Methods for wastewater characterization in activated sludge modelling, IWA publishing

Melgoza RM, Cruz A, Buitrón G (2004) Anaerobic/aerobic treatment of colorants present in textile effluents. Water Sci Technol 50(2):149–155

Mino T, Van Loosdrecht M, Heijnen J (1998) Microbiology and biochemistry of the enhanced biological phosphate removal process. Water Res 32(11):3193–3207

Mousavian S, Seyedsalehi M, Paladino O, Sharifi P, Kyzas GZ, Dionisi D, Takdastan A (2019) Determining biokinetic coefficients for the upflow anaerobic sludge blanket reactor treating sugarcane wastewater in hot climate conditions. Int J Environ Sci Technol 16(5):2231–2238

O'neill C, Lopez A, Esteves S, Hawkes F, Hawkes D and Wilcox S, (2000) Azo-dye degradation in an anaerobic-aerobic treatment system operating on simulated textile effluent. Appl Microbiol Biot 53(2):249–254

O'neill C, Hawkes F, Hawkes D, Esteves S and Wilcox S, (2000) Anaerobic–aerobic biotreatment of simulated textile effluent containing varied ratios of starch and azo dye. Water Res 34(8):2355–2361

Oehmen A, Zeng RJ, Yuan Z, Keller J (2005) Anaerobic metabolism of propionate by polyphosphate-accumulating organisms in enhanced biological phosphorus removal systems. Biotechnol Bioeng 91(1):43–53

Paździor K, Wrębiak J, Klepacz-Smółka A, Gmurek M, Bilińska L, Kos L, Sójka-Ledakowicz J, Ledakowicz S (2017) Influence of ozonation and biodegradation on toxicity of industrial textile wastewater. J Environ Manage 195:166–173

Punzi M (2015) Treatment of textile wastewater by combining biological processes and advanced oxidation. Lund University, Department of Biotechnology

Rongrong L, Xujie L, Qing T, Bo Y, Jihua C (2011) The performance evaluation of hybrid anaerobic baffled reactor for treatment of PVA-containing desizing wastewater. Desalination 271(1–3):287–294

Saratale RG, Saratale GD, Chang J-S, Govindwar S (2011) Bacterial decolorization and degradation of azo dyes: a review. J Taiwan Inst Chem E 42(1):138–157

Sathya U, Nithya M, Balasubramanian N (2019) Evaluation of advanced oxidation processes (AOPs) integrated membrane bioreactor (MBR) for the real textile wastewater treatment. J Environ Manage 246:768–775

Schönberger H, Schäfer T (2003) Best available techniques in textile industry. Federal Environmental Agency, Berlin

Shaul GM, Holdsworth TJ, Dempsey CR, Dostal KA (1991) Fate of water soluble azo dyes in the activated sludge process. Chemosphere 22(1–2):107–119

Shaw C, Carliell C, Wheatley A (2002) Anaerobic/aerobic treatment of coloured textile effluents using sequencing batch reactors. Water Res 36(8):1993–2001

Spagni A, Casu S, Grilli S (2012) Decolourisation of textile wastewater in a submerged anaerobic membrane bioreactor. Bioresource Technol 117:180–185
Sponza D, Işik M (2002) Decolorization and azo dye degradation by anaerobic/aerobic sequential process. Enzyme Microb Tech 31(1–2):102–110
Velasco-Garduño O, Mendoza-Reséndiz A, Fajardo-Ortiz C, Beristain-Cardoso R (2019) Simultaneous ammonia and organic matter removal from industrial wastewater in a continuous novel hybrid carrousel bioreactor. Int J Environ Sci Te 16(7):3429–3436
Verma AK, Nath D, Bhunia P, Dash RR (2016) Application of Ultrasonication and Hybrid Bioreactor for Treatment of Synthetic Textile Wastewater. J Hazard Toxic Radioact Waste 21(2):04016018
Von Sperling M and de Lemos Chernicharo CA (2017) Biological wastewater treatment in warm climate regions. IWA publishing
Wang Z, Xue M, Huang K and Liu Z (2011) Advances in treating textile effluent. InTech
Yan L, Liu Y, Ren Y, Wang X, Liang H, Zhang YJB, engineering b, (2013) The effect of pH on the efficiency of an SBR processing piggery wastewater. Biotechnol Bioprocess Eng 18(6):1230–1237
Yasar A, Tabinda AB (2010) Anaerobic treatment of industrial wastewater by UASB reactor integrated with chemical oxidation processes; an overview. Pol J Environ Stud 19(5):1051–1061
Yen F-C, Chang T-C, Hu CC, Laohaprapanon S, Natarajan TS, You S-J (2016) Feasibility of combined upflow anaerobic sludge blanket-aerobic membrane bioreactor system in treating purified terephthalic acid wastewater and polyimide membrane for biogas purification. J Environ Chem Eng 4(4):4113–4119
Zhang TC, Fu Y, Bishop PL, Kupferle M, FitzGerald S, Jiang HH, Harmer C (1995) Transport and biodegradation of toxic organics in biofilms. J Hazard Mater 41(2–3):267–285
Zhidong L, Yong Z, Xincheng X, Lige Z, Dandan Q (2009) Study on Anaerobic/Aerobic Membrane Bioreactor Treatment for Domestic Wastewater. Pol J Environ Stud 18(5):1

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