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Performance and cost-benefit analysis of anaerobic moving bed biofilm reactor for pretreatment of textile wastewater

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Abstract−Performance of an anaerobic moving bed biofilm reactor (AnMBBR) was evaluated for pretreatment of real textile desizing wastewater at organic loading rate (OLR) of 1±0.05 to 6.3±0.37 kgCOD/m^3/d. After OLR optimization, the performance of AnMBBR was evaluated for biodegradation of reactive dyes. AnMBBR was operated under a mesophilic temperature range of 30 to 36 °C, while the oxidation-reduction potential (ORP) and pH were in the range of 504 to 594 (-mV) and 6.98 to 7.28, respectively. By increasing the OLR from 1±0.05 to 6.3±0.37 kgCOD/m^3/d, COD and BOD$_5$ removal was decreased from 84 to 39% and 89 to 49%, respectively. While the production of biogas was increased from 0.12 to 0.83 L/L·d up to an optimum OLR of 4.9±0.43 kgCOD/m^3/d. With increase in the dye concentration in the feed, COD, BOD$_5$, color removal and biogas production reduced from 56, 63, 70% and 0.65 L/L·d to 34, 43, 41% and 0.08 L/L·d, respectively. Based on the data obtained, a cost-benefit analysis of AnMBBR was also investigated for the pretreatment of real textile desizing wastewater. Cost estimation of anaerobic pretreatment of textile desizing wastewater indicated a net profit of 21.09 million PKR/yr (114,000 €/yr) and a potential payback period of 2.54 years.

Keywords: Anaerobic Moving Bed Biofilm Reactor, Organic Loading Rate, COD Removal, Color Removal, Biogas Production, Cost-benefit Analysis

INTRODUCTION

The textile industry plays a significant role in the economic development of a country. However, it is also one of the largest producers of wastewater with high concentration of organic and inorganic pollutants, such as chemical oxygen demand (COD), biological oxygen demand (BOD$_5$), dyes and some other chemicals like acids, base, oil and grease, thickeners, urea, detergent, surfactants, and reducing agents [1]. If the textile wastewater is not treated properly, it might cause severe environmental problems and public health concerns [2,3]. Textile production includes desizing, scouring, bleaching, mercerizing, dyeing, printing and finishing processes. Desizing alone generates up to 50% of total COD load of textile industry within the 15% of total wastewater discharged from the industry [4]. Wastewater generated from scouring is high in volume, with high alkalinity, organic concentration and pH. Bleached wastewater is also produced in large quantity; however it has relatively lower contaminants. Mercerized wastewater has a high alkali content with NaOH levels ranging from 3 to 5% [5]. Dye wastewater has a considerable variation in both quality and quantity. Wastewater generated from the dyeing process contains about 20 to 30% of the reactive dyes applied to fabrics [6]. Printing wastewater is small in volume and contains a small amount of slurry, color, BOD$_5$, and COD concentrations [5,7]. Finishing wastewater mainly contains fiber tow, resin, formaldehyde and oiling agent in relatively small amount [5]. Effluent from desizing and dyeing processes are the major contributors of COD and color in textile wastewater.

In Pakistan, the centralized aerobic activated sludge process (ASP) is widely used for the treatment of textile wastewater [8]. Due to the high COD concentration and higher stability of modern synthetic dyes, the aerobic ASP is ineffective for the complete removal of color and requires aeration in bulk for the degradation of organics. Numerous combined biological and physicochemical processes and other treatment methods have been proposed, developed and applied for the treatment of textile wastewater. However, a separate and dedicated pretreatment facility of desizing and dyeing processes is facile, effective and economical compared to combined centralized treatment of textile wastewater. The aim of pretreatment is to increase the decolorization efficiency and COD removal with lowering the aeration cost in subsequent aerobic treatment. Various treatment methods have been used for pretreatment of desizing and dyeing wastewater, such as chemical oxidation, catalytic thermal treatment, membrane filtration, coagulation-flocculation, adsorption, and biological treatment [1,9-12]. However, the high initial capital cost as well as the operating and maintenance costs render these techniques less appealing for textile industries to adopt. Since

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desizing wastewater contains a high concentration of organics, therefore, it has been reported as a potential source for bioenergy production through anaerobic digestion [4,13,14]. On the other hand, anaerobic digestion imparts the maximum degradation of complex color compounds of industrial wastewater efficiently [15].

Various studies relevant to anaerobic digestion of desizing and dyeing wastewater are available in the literature [4,13,16-20]. Lin, et al. [4] investigated the performance of anaerobic digestion with granular activated carbon for the treatment of textile desizing wastewater. They achieved maximum COD removal of 90% with bioenergy production of 16.5 kJ/L/d. Rongrong et al. [18] investigated the performance of hybrid anaerobic baffled reactor for desizing wastewater treatment. They achieved specific methane yield of 0.30 $m^3/kgCOD_{removed}$ with maximum COD removal of 42%. Opwis et al. [13] used an anaerobic reactor for organic load reduction and biogas production from desizing wastewater. They reported maximum organic removal of 85% with biogas production of 27 L per L of textile desizing wastewater having methane content of 60%. Lee et al. [21] used an anaerobic reactor for biological decolorization of reactive dyebaths wastewater. They found that the presence of non-biodegradable complex compounds in textile wastewater imparted color to the wastewater that can be treated effectively by anaerobic process due to slow degradation. However, most of the studies reported have been carried out at laboratory scale reactors often using synthetic wastewater. The aim of such studies was to investigate the impact of various controlled parameters; however, the results are not scalable.

Anaerobic moving bed biofilm reactor (AnMBBR) has numerous advantages as one of the high-rate anaerobic reactors, e.g., high treatment efficiency, high stability for shock loading, low energy consumption, simple design and utilization of whole volume of bioreactor [22,23]. As an advanced system for treatment of industrial wastewater, the AnMBBR is widely used for the treatment of milk permeate from dairy industry [24], brewery wastewater [22], winery wastewater [25], municipal wastewater [26], oil contaminated wastewater [27] and synthetic glucose-containing wastewater [28]. However, to the best of the authors' knowledge, no study on the treatment of desizing and dyeing wastewater using AnMBBR has been reported as yet. Therefore, it is necessary to evaluate the performance of a pilot scale AnMBBR for pretreatment of textile desizing and dyeing wastewater.

The aim of this study is to examine the performance of pilot scale AnMBBR for the pretreatment of textile desizing wastewater. The effects of organic loading rate (OLR) or hydraulic retention time (HRT) on the AnMBBR performance (i.e., COD removal, BOD_5 removal, volatile fatty acids (VFA) production, biogas production and composition) were investigated. After the OLR optimization, the performance of AnMBBR was also evaluated with the increase in dye concentration in the feed for biodegradation of reactive dyes. Based on the results obtained from the pilot study, a cost-benefit analysis was provided for a full scale anaerobic MBBR.

MATERIALS AND METHODS

1. Experimental Setup

A pilot scale AnMBBR was used for the pretreatment of real textile desizing and dyeing wastewater. The reactor was operated under on-site conditions in Kohinoor Textile Mills Limited (KTML), Rawalpindi, Pakistan. A schematic diagram of anaerobic plant is in Fig. 1(a) and a pictorial view of the pilot plant with the plastic carrier material is in Fig. 1(b). A cylindrical bioreactor with a diameter of 1 m, height of 1.78 m and active digester volume of 1.4 m^3 was used as AnMBBR in this study. The plant was designed and constructed by A3 water solution GmbH, Germany. The bioreactor was mainly constituted of inlet for feeding, mounted motor with double impeller for stirring, a recirculation column, glass window on top for observation, outlet for the biogas and a drain valve. Wastewater for AnMBBR was collected in two intermediate bulk containers (IBC) from the first washing box of the bleaching and dyeing line, where the highest concentration of the COD and color was expected and then transferred to the pilot anaerobic plant by a fork lifter. After 16-20 hours of collection, the collected wastewater was transferred to the feed tank through a filter (250 μm pore size) using a liquid transfer pump (Drum pump Lutz B2 Vario, Germany). A motor for the stirring was installed in the feed tank to maintain uniform conditions within the feed tank. A peristaltic pump (Cole Parmer, 77200-62, Masterflex, USA) was used as a feed pump to transfer wastewater from feed tank to AnMBBR. For biofilm growth, AnMBBR was filled, with 35% of the bioreactor volume, by a plastic media (Pearl®, EvU - Innovative Umwelttechnik GmbH, Germany) having specific surface area of 700 m^2/m^3 and density of 0.98 g/cm^3. Wastewater of the bioreactor was recirculated by a pump (Cole-Parmer MD 025-6L, Germany) with a flow rate of 0.15 m^3/h. Another pump (Peristaltic MP2-R, Italy) linked to a pH sensor was used for the pH adjustment of AnMBBR. Biogas generated from the AnMBBR was passed through a gravel filter and collected into a biogas bag (BioGas Backpack, Energy GmbH, Germany) with a capacity of 1.2 m^3 to burn it later. The generated biogas was measured by an inline gas flow meter (G4-RF1, Germany). The immersion heater and K-Type thermocouple were provided in the recirculation column of AnMBBR to maintain a minimum temperature of 30 °C inside the bioreactor, particularly during the winter season and at night. During winter, the temperature of AnMBBR was fixed at 30 °C and during summer, the temperature fluctuated between 30 and 36 °C. Three sampling points were also provided for the collection of influent, bioreactor and effluent samples.

2. Operating Conditions

AnMBBR was operated in three different phases: a) startup or acclimatization phase, b) optimization of OLR or HRT for pretreatment of real textile desizing wastewater, and c) biological degradation of high concentrated dyes with the mixture of desizing wastewater.

Approximately 50 kg of cow manure obtained from local farm was used as a seed sludge for AnMBBR. Cow manure was mixed with water and sieved; the as-obtained filtered emulsion was then transferred to the bioreactor. During the acclimatization period, semi-continuous (intermittent) feeding was provided to AnMBBR to avoid rapid VFA accumulation and pH reduction. AnMBBR was fed continuously as a significant amount of biogas was produced. After acclimatization, AnMBBR performance was evaluated at different OLR of 1±0.05 to 6.3±0.37 $kgCOD/m^3/d$ and HRT ranged

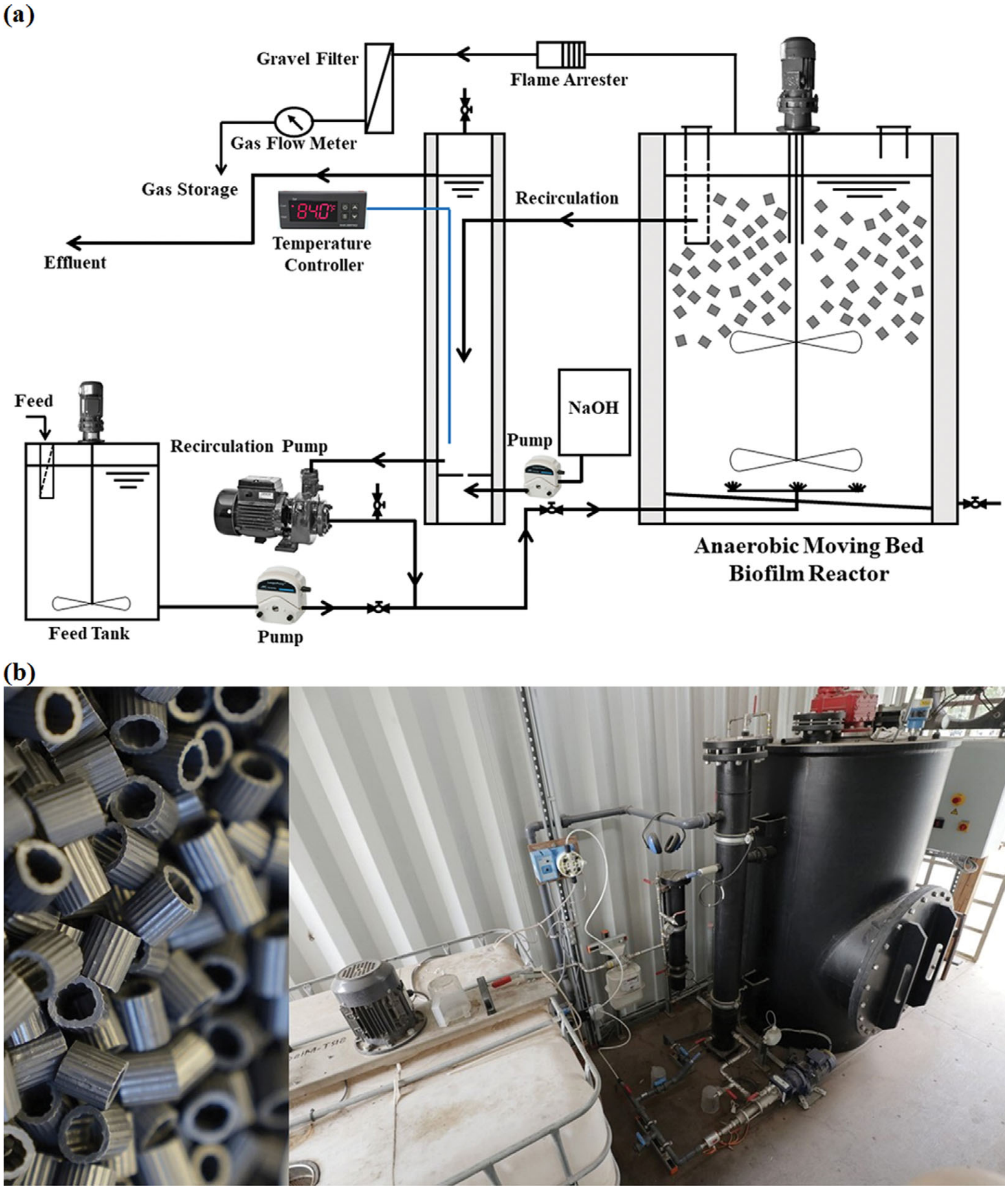

Fig. 1. (a) Schematic diagram of anaerobic plant and (b) pictorial view of the carrier material (left) and anaerobic plant (right).

Table 1. Operating conditions for AnMBBR

	Optimization phase on desizing wastewater		Performance and biodegradation of reactive dyes	
	HRT (days)	OLR (kgCOD/m^3/d)	OLR/HRT	Dyeing-desizing wastewater ratio (v/v)
Startup and acclimatization phase	32	1±0.05	Optimized OLR/HRT from previous phase	1 : 9
	20	1.5±0.06		
	16	1.9±0.09		2 : 8
	12	2.4±0.29		
	10	2.9±0.33		3 : 7
	8	3.7±0.35		
	6	4.9±0.43		4 : 6
	5	6.3±0.37		

Table 2. Textile desizing and dyeing wastewater characteristics

Parameters	Unit	Textile desizing wastewater	Textile dyeing wastewater
BOD_5	mg/L	21,450±8,426	2,685±902
COD	mg/L	34,790±11,375	8,457±2,266
Color	Pt-Co	374±93	4,182±544
Sulfate	mg/L	218±159	690±276
TN	mg/L	221±177	1,764±374
TP	mg/L	21±11	29±5
pH	--	6.4±1.2	8.7±1.6

from 32 to 5 days. It is the normal working range for anaerobic reactors to achieve a steady process; however, it may vary depending on the type of wastewater and operating conditions [29,30]. These OLRs can be achieved either by increasing the feed concentration, keeping the flow rate constant, or by increasing the flow rate slowly while holding the feed concentration constant. In this study, the feed concentration of real textile desizing wastewater could not be controlled as it depends on the concentration of applied sizing and desizing chemicals, types of fabric and flow rate in the wash boxes. OLR of AnMBBR was adjusted by gradually increasing the feed flow rate to the bioreactor. The system was operated continuously until a steady-state condition at each OLR was achieved. Table 1 shows the operating conditions of AnMBBR in this study. After optimizing OLR of AnMBBR, textile dyeing wastewater with a combination of desizing wastewater was used to check the performance and biodegradation of reactive dyes. Reactive dyeing wastewater was added to the desizing wastewater to prepare feed solution with dyeing-desizing wastewater ratio (v/v) of 1 : 9. Once the reactor reached steady-state, the proportion of the reactive dye wastewater in dyeing-desizing wastewater ratio (v/v) was increased stepwise from 1 : 9 to 4 : 6.

3. Characteristics of Wastewater

Characteristics of the textile desizing and dyeing wastewater generated in KTML industry are summarized in Table 2. The characteristics of wastewater are highly variable over time due to change of fabric type and water flow in wash boxes. Keeping in mind the concept of equalization tank for the full-scale plant design, every new wastewater batch was always mixed with the existing wastewater in the feed tank for the continuous feeding to AnMBBR.

4. Analytical Methods

Parameters like COD, color, pH, VFA, alkalinity and oxidation reduction potential (ORP) were tested at a one-day interval. Temperature and the biogas production were measured on a daily basis. BOD_5 removal and analysis for the methane composition of the biogas were done at every stable state before changing the operating condition. Samples for the analysis were collected from the influent, recirculation and effluent of the anaerobic plant.

COD, BOD_5, VFA, and alkalinity were analyzed as per the Standard Method [31]. Color of wastewater was measured after filtering the sample based on the APHA platinum-cobalt standard method. ORP and pH were checked by using a portable meter (Hanna Instruments Ltd., HI 83141, UK). Methane composition of the biogas was checked with the gas chromatography coupled with a thermal conductivity detector (Shimadzu, GC 2010 plus, Japan).

RESULTS AND DISCUSSION

1. AnMBBR Performance for Biodegradation of Desizing Wastewater

1-1. Chemical Oxygen Demand, VFA and Biogas Production

The results obtained from AnMBBR are illustrated in Fig. 2 and the average values of the measured parameters at steady-state con-

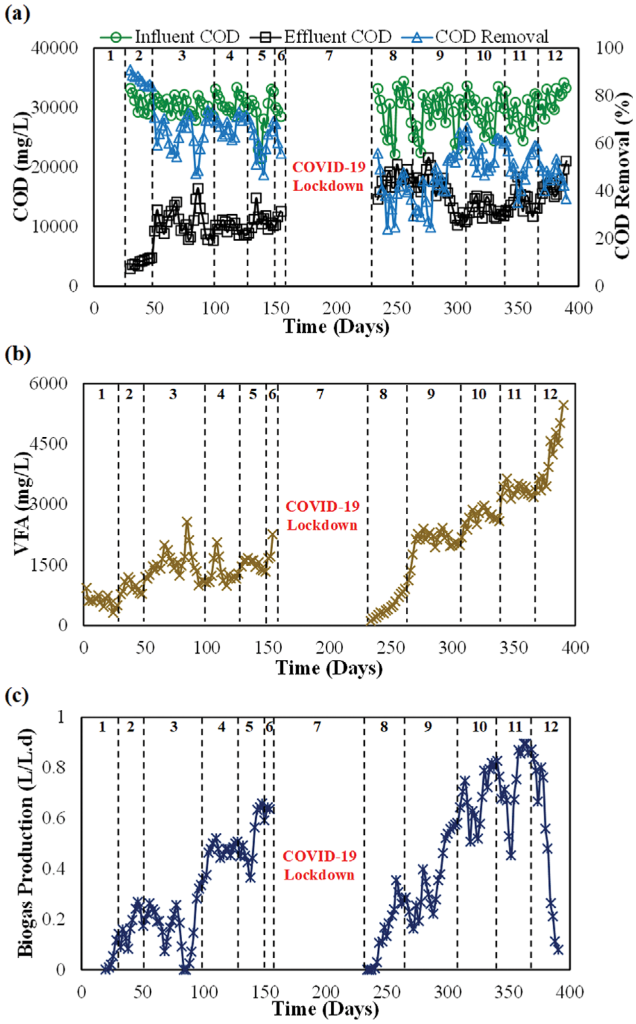

Fig. 2. (a) Influent, effluent COD and COD removal, (b) VFA accumulation and (c) biogas production from AnMBBR for treatment of desizing wastewater.

Table 3. Performance of AnMBBR in different stages at different OLR or HRT

Stage	1	2	3	4	5	6	7	8	9	10	11	12
OLR (kgCOD/m^3/d)	--	**1±0.05**	**1.5±0.06**	**1.9±0.09**	**2.4±0.29**	**2.9±0.32**	**0**	**1.5±0.18 to 2.6±0.21**	**2.9±0.33**	**3.7±0.35**	**4.9±0.43**	**6.3±0.37**
HRT (days)	--	**32**	**20**	**16**	**12**	**10**	**0**	**20 to 12**	**10**	**8**	**6**	**5**
Run time (days)	1-28	29-48	49-98	99-126	127-148	149-154	155-232	233-262	263-306	307-340	341-366	367-392
Influent COD (mg/L)	--	30,228	29,658	30,946	32,202	--	--	--	30,660	31,638	32,754	33,296
Effluent COD (mg/L)	--	4,738	8,148	9,000	10,680	--	--	--	11,446	12,228	13,798	20,370
COD removal (%)	--	84	73	71	67	--	--	--	63	61	58	39
Influent BOD$_5$ (mg/L)	--	16,650	12,322	17,908	16,041	--	--	--	10,920	14,493	17,984	13,794
Effluent BOD$_5$ (mg/L)	--	1,830	1,110	3,044	3,690	--	--	--	3,386	3,768	6,294	7,034
BOD$_5$ removal (%)	--	89	91	83	77	--	--	--	69	74	65	49
Biogas (L/L·d)	0.12	0.25	0.31	0.48	0.65	--	--	--	0.57	0.74	0.83	0.08
Methane content (%)	--	74	71	77	69	--	--	--	61	71	74	51
VFA (mg/L)	416	828	1,070	1,220	1,366	--	--	--	2,026	2,632	3,230	5,002
Alkalinity (mg/L)	5446	4,858	5,264	5,984	6,074	--	--	--	5,728	6,344	7,340	10,208
pH	7.26	7.11	7.3	6.98	7.13	--	--	--	7.28	7.16	7.09	7.01
ORP (-mV)	594	565	534	557	585	--	--	--	504	561	573	539

ditions are summarized in Table 3. Vertical lines in graphs illustrate the stages at which the operating condition of AnMBBR was changed. During the acclimatization stage, intermittent feeding was provided to AnMBBR with real textile desizing wastewater and only VFA and biogas production from bioreactor were measured. VFA production started from day 1 and, consequently, accumulation of VFA in AnMBBR was increased until the biogas production was started. Continuous feeding to bioreactor was initiated from day 30 when AnMBBR produced a significant amount of the biogas. Thereafter, the wastewater samples were collected from influent and effluent of AnMBBR for various analyses. Influent and effluent COD of AnMBBR were in the range of 21,475 to 34,437 mg/L and 2,993 to 21,624 mg/L, respectively. While VFA and biogas production varied from 114 to 5,468 mg/L and 0 to 0.90 L/L·d, respectively.

After acclimatization, the performance of AnMBBR was evaluated to estimate the minimum HRT and maximum OLR. In stage 2, the initial OLR of AnMBBR was set to 1±0.05 kgCOD/m^3/d and HRT of 32 days. The COD removal, VFA and biogas production under stabilized condition from AnMBBR were 84%, 828 mg/L and 0.25 L/L·d, respectively. In stage 3, COD removal and biogas production were initially reduced to 59% and 0.17 L/L·d, respectively. While VFA production was initially increased to 1,472 mg/L due to the shock received to microorganisms by increasing the OLR to 1.5±0.06 kgCOD/m^3/d. Before stabilizing the bioreactor in stage 3, disturbance in the performance and scum production in AnMBBR was observed on day 60 and day 82. The results indicated that scum production reduced COD removal accompanied by increased acidification that led to retardation in methanogenesis.

There are two bleaching plants in the textile industry and wastewater was collected from both plants initially and used. Disturbance in the performance of AnMBBR and scum production was due to the utilization of recycled wastewater from bleaching plant where post bleaching wastewater was being used in the wash boxes of the desizing. This implies that bleaching wastewater had a toxic effect on anaerobic microorganisms due to the high level of chlorides and peroxide. Similar observation was also reported by Sarayu and Sandhya [32]. Thereafter, wastewater sample was collected only from the bleaching unit where freshwater was being used for washing. AnMBBR took a longer time to stabilize after manual removal of scum and replacing the feed wastewater. It was found that the COD removal efficiency and biogas production increased up to 73% and 0.31 L/L·d, respectively. While VFA concentration in the AnMBBR reduced to 1,070 mg/L when the bioreactor was stabilized.

Later, OLR was further increased to 1.9±0.09 kgCOD/m^3/d for stage 4. This created a minor disturbance in the performance of AnMBBR. COD removal and biogas production were relatively stable at 71% and 0.48 L/L·d. VFA concentration was initially increased to 2,065 mg/L and then reduced to a lower value (1,220 mg/L) as the bioreactor adapted to the new condition. This result indicates that the AnMBBR was efficient for absorbing variations in OLR. In the next stage (stage 5), OLR was increased to 2.4±0.29 kgCOD/m^3/d by reducing the HRT to 12 days. COD removal and biogas production gradually stabilized to 67% and 0.65 L/L·d, respectively. VFA concentration in AnMBBR was initially increased and then gradually stabilized to 1,366 mg/L. In stage 6, OLR was further increased to 2.9±0.32 kgCOD/m^3/d by reducing the HRT to 10 days. However, before stabilizing AnMBBR at OLR of 2.9±0.32 kgCOD/m^3/d, the industry was closed due to COVID-19 lockdown and AnMBBR was not fed for 76 days (as shown in stage 7). Accumulated VFA was consumed and a total of 2,170 L of biogas was produced during this time.

The study had to be started again from lower OLR of 1.5±0.18 kgCOD/m^3/d, which was gradually increased to 1.8±0.31, 2.6±0.21, 2.9±0.33 kgCOD/m^3/d with an interval of ten days. AnMBBR was started again from lower OLR to avoid any shock overload and inhibition of the bioreactor. In stage 9, at OLR of 2.9±0.33 kgCOD/

m^3/d, the AnMBBR took a longer time for biodegradation before final stabilization. It was found that the efficiency of COD removal was 63%, VFA and biogas production was 2,026 mg/L and 0.57 L/L·d when AnMBBR was stabilized. However, the prolonged time taken by the bioreactor until stabilization was possibly due to the shock obtained during the random change of OLR. In stages 10 and 11, OLR was further increased to 3.7±0.35 and 4.9±0.43 kgCOD/m^3/d by increasing the feed flow rate and reducing the HRT to 8 and 6 days, respectively. At both OLRs, a minor disturbance was observed for COD removal, VFA and biogas production of AnMBBR. At stabilized conditions, COD removal was 61 and 58%, VFA production was 2,632 and 3,230 mg/L and biogas production was 0.74 and 0.83 L/L·d for OLR of 3.7±0.35 and 4.9±0.43 kgCOD/m^3/d, respectively. However, with a further increase in OLR to 6.3±0.37 kgCOD/m^3/d (in stage 12), COD removal was drastically reduced to 39%. Biogas production was initially increased to 0.87 L/L·d and continuously reduced thereafter. Instability of AnMBBR was observed due to the continuous increase in the VFA concentration, which was increased above 5,000 mg/L. Considering all these conditions, it was difficult for the AnMBBR to stabilize and therefore the feeding process had to be stopped.

A continuous increase in OLR with textile desizing wastewater was maintained (from stage 2 to stage 12) until the highest reduction in COD removal and biogas production to 39% and 0.08 L/L·d at OLR of 6.3±0.37 kgCOD/m^3/d were observed. In the OLR range of 1±0.05 to 4.9±0.43 kgCOD/m^3/d (from stage 2 to stage 11), the average COD removal and biogas production were found to be fairly stable as shown in Fig. 2. Variations in COD removal, VFA and biogas production were observed at the start of each stage due to the shock received to the microorganisms by increasing the feed flow rate. Similar trend of the COD removal, VFA and biogas production at different OLR was reported in previous studies [33-37]. Once microorganisms adapted to the new condition, relatively stable COD removal efficiency and biogas production were observed, and VFA concentration within AnMBBR reduced to a lower value.

Based on the obtained results, maximum OLR and minimum HRT for anaerobic pretreatment of textile desizing wastewater were 4.9±0.43 kgCOD/m^3/d and 6 days, respectively. At a higher OLR of 6.3±0.37 kgCOD/m^3/d, instability of AnMBBR occurred due to the hydraulic overloading and washed out of slow growing methane producing bacteria. Bi et al. [34] revealed that the wash out of methanogenic bacteria causes VFA accumulation, and acidic bacteria become dominant in the reactors. Banu et al. [38] observed that the methanogenic bacterial growth was also reduced due to the acidification that has been reported to make the conditions unfavorable for methanogenesis and process efficiency decreases. Therefore, a higher VFA concentration of more than 5,000 mg/L in AnMBBR indicated that the bioreactor was overloaded and resulted in reduction in biogas production and COD removal efficiency.

1-2. Biological Oxygen Demand (BOD_5) and Methane Content in the Biogas

BOD_5 and methane content in the biogas were checked prior to changing the operating condition of AnMBBR (in stages 2 to 5 and 9 to 12). Table 3 shows the value of influent and effluent biochemical oxygen demand (BOD_5) with respective BOD_5 removal efficiencies at different OLR under stabilized conditions. Textile desizing wastewater exhibited BOD_5 to COD ratio of 0.55 to 0.71. The variation of BOD_5 to COD ratio in the feed tank was 0.38 to 0.58 due to the rapid degradation of the BOD_5 as compared to COD. Despite the significant fluctuation in the influent BOD_5 concentration, the BOD_5 removal was observed as 91 to 65% for the organic loading rates of 1±0.05 to 4.9±0.43 kgCOD/m^3/d. But it decreased to 49% at the highest OLR of 6.3±0.37 kgCOD/m^3/d (in stage 12). This also shows that the organic overload occurred at OLR of 6.3±0.37 kgCOD/m^3/d. This could be attributed to lower microbial activity (lack of methanogenic microbial concentration) at highest OLR. Furthermore, Musa et al. [39] also revealed a similar reduction of BOD_5 removal due to the shock loading.

Methane content in the biogas under stabilized conditions is shown in Table 3. In stages 2 to 5, corresponding to the OLR of 1±0.05 to 2.90±0.32, methane content was between 69 to 77%. In stage 9, methane content in the biogas was 61%, which was later increased to 71 and 74% in stages 10 and 11, respectively. In stage 9, sample for biogas analysis was collected in a gas bag when plant was running under stable conditions, but analysis was performed later when the university opened after the COVID-19 lockdown. In stage 12, at higher OLR of 6.3±0.37 kgCOD/m^3/d, methane content in the biogas was reduced to 51%.

1-3. Alkalinity, pH and Oxidation-reduction Potential of AnMBBR

Alkalinity, pH and oxidation-reduction potential of AnMBBR were also monitored throughout the research period. To avoid disturbance in the performance, such as the complete loss of microbial activity, adequate monitoring and control of the anaerobic process are required. Among other environmental and operating conditions, pH is the most sensitive parameter that should be carefully monitored. pH indicates the stability of the anaerobic reactor and the variation depends on the buffering capacity of the system [40]. During the study period, feed pH of AnMBBR was in the range of 4.9 to 7.1. Whereas anaerobic reactors performed effectively in the pH range of 6.8 to 7.2, the pH of AnMBBR was automatically adjusted with the dosing pump connected with the pH sensor of the recirculation column. Sodium hydroxide (NaOH) was used for pH adjustment which acted as a buffer and the methanogens were not exposed to low pH during shock received due to increase in the OLR. It can be observed from Table 3 that the pH within the AnMBBR always remained in the range of 6.98 to 7.28. VFA and alkalinity ratio is also an important parameter to check the buffering capacity of the anaerobic reactor. By increasing the OLR, the VFA concentration increased and alkalinity was consumed, indicating that the AnMBBR might be approaching to failure. However, AnMBBR recovered quickly due to adjustment by dosing of NaOH and later on the VFA was consumed. VFA and alkalinity ratio remained below 0.5 throughout the study even at higher OLR. Oxidation-reduction potential provides an important information on the oxidation-reduction condition of microbial system. Extremely reducing environment (ORP <-300) has been reported to be favorable for anaerobic systems. In this study, the ORP value of AnMBBR sample fluctuated within the range of −504 to −594 mV, which favored the growth of microorganisms.

2. AnMBBR Performance for Biodegradation of Reactive Dyes

After overloading of AnMBBR at HRT of 5 days or OLR of

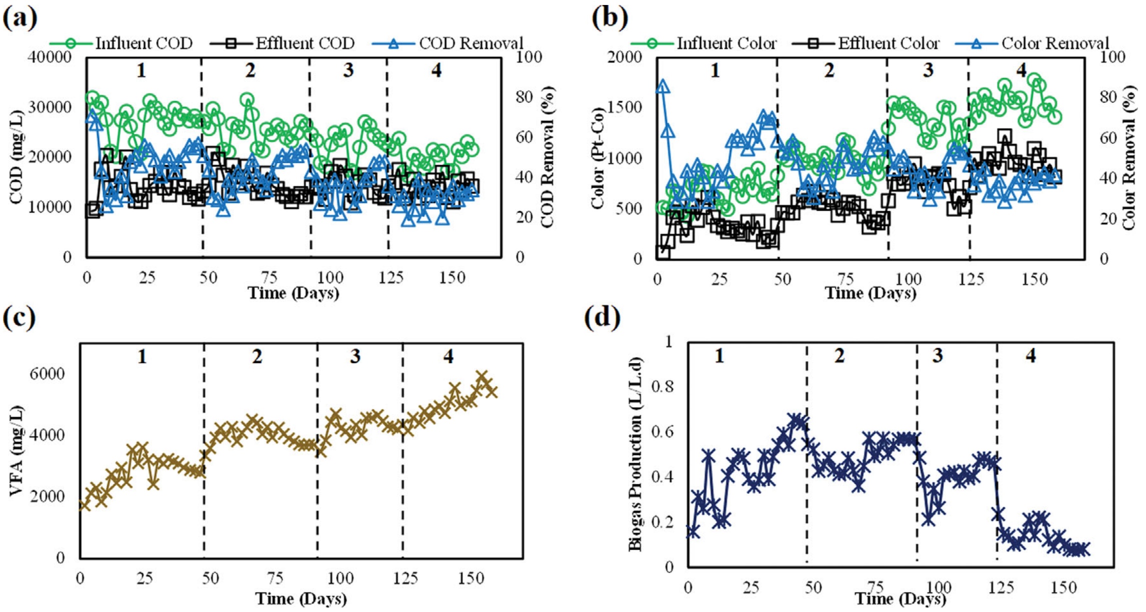

Fig. 3. (a) Influent, effluent COD and COD removal, (b) influent, effluent color and color removal, (c) VFA accumulation and (d) biogas production from AnMBBR for treatment of dyeing wastewater.

6.3±0.37 kgCOD/m^3/d, the feeding was stopped until excess VFA biodegraded and microbial communities recovered from inhibition. However, during this time, VFA and biogas production were still measured. It was observed that the production of biogas increased gradually with a reduction of VFA, indicating a recovery of methane producing bacteria. This was also confirmed by the analysis of methane content in biogas at the completion of the stage, which revealed an increase to 61%. Based on the recovery from inhibition, feeding of textile desizing wastewater to AnMBBR was started again at HRT of 6 days and OLR of 5.09±0.57 kgCOD/m^3/d. Before feeding of the reactive dye wastewater, average COD removal efficiency and production of biogas from AnMBBR were 59% and 0.75 L/L·d, respectively, at steady-state condition.

Fig. 3(a) and (b) presents COD and color of influent and effluent as well as removal efficiency of both from the anaerobic MBBR. In the first step, dyeing wastewater was added to the desizing wastewater to prepare the mixed feed solution with a dyeing-desizing wastewater ratio (v/v) of 1 : 9 with OLR of 4.7±0.54 kgCOD/m^3/d. At a similar HRT of 6 days, OLR of AnMBBR was decreased due to dilution of desizing wastewater with low COD of reactive dye wastewater. At the beginning of the continuous operation, the high color removal efficiency (higher than 80%) seems to be due to the dilution within AnMBBR till a complete HRT. Color removal efficiency decreased with time, and ultimately increased once sludge was acclimatized. The average COD and color removal efficiency at the end of first step were 56 and 70%, respectively. Whereas the average biogas production and VFA concentration in AnMBBR were 0.65 L/L·d and 2,845 mg/L, respectively. On day 47, increasing the volume of reactive dye wastewater in feed to ratio of 2 : 8, increased reactive dye concentration in feed to 929 Pt-Co and reduced the OLR to 4.3±0.45 kgCOD/m^3/d. Initially, COD and color removal efficiency decreased to 24 and 31%, respectively, while the VFA concentration sharply increased to 4,284 mg/L. COD and color removal efficiency stabilized to 53 and 59% and VFA concentration reduced to 3,702 mg/L, as AnMBBR adapted to the new condition. While the biogas production initially reduced to 0.41 L/L·d and stabilized to 0.57 L/L·d. On day 91, increasing the volume of reactive dye wastewater in feed to 3 : 7 reduced the OLR to 3.8±0.52 kgCOD/m^3/d. Under steady-state condition, COD and color removal efficiency stabilized to 49 and 53%, respectively. While VFA and biogas production stabilized to 4,263 mg/L and 0.47 L/L·d, respectively. On day 123, the subsequent increase in dye wastewater volume in feed to 4 : 6, the average reactive dye concentration in feed increased to 1,479 Pt-Co and OLR reduced to 3.4±0.37 kgCOD/m^3/d. AnMBBR performance was drastically affected in terms of COD and color removal efficiency, which were reduced to 34 and 41%, respectively. VFA concentration sharply increased to 5,680 mg/L, while the biogas production significantly reduced to 0.07 L/L·d. This high level of VFA of AnMBBR resulted in reduced COD and color removal efficiency and biogas production. The VFA/Alkalinity ratio varied between 0.3 and 0.6, indicating the moderate instability of the AnMBBR. It was reported previously that VFA concentration also increased with the loading rate of dye wastewater. It indicates that increase in volume of dyeing wastewater in feed is inhibitive to methane producing bacteria, which consume VFA for metabolism [41].

In general, low volume of dyeing wastewater in feed resulted in better color removal efficiency, which indicates that anaerobic bacteria can effectively decolorize textile dyes if the toxic compounds found in the reactive dye wastewater or generated during anaerobic treatment (e.g., aromatic amines) are present in relatively low concentration. Textile dye wastewater contains a huge amount of nitrogen compound due to use of urea during dyeing processes. Main purpose of urea during continuous application of dyes on fabric is to increase the dye solubility in reaction medium and control water evaporation during swelling and drying of cotton, thereby

Table 4. Performance of AnMBBR on biodegradation of reactive dyes

Stage	**1**	**2**	**3**	**4**
Dyeing wastewater volume in feed (%)	**10**	**20**	**30**	**40**
Desizing wastewater volume in feed (%)	**90**	**80**	**70**	**60**
OLR (kgCOD/m^3/d)	**4.7±0.54**	**4.3±0.45**	**3.8±0.52**	**3.4±0.37**
Run time (days)	1-46	47-90	91-122	123-158
Influent COD (mg/L)	27,659	26,228	24,410	21,661
Effluent COD (mg/L)	12,173	12,404	12,420	14,518
COD removal (%)	56	53	49	34
Influent color (Pt-Co)	660	929	1,198	1,479
Effluent color (Pt-Co)	200	378	562	868
Color removal (%)	70	59	53	41
BOD$_5$ removal (%)	63	55	51	43
Biogas (L/L·d)	0.65	0.57	0.47	0.07
Methane content (%)	66	56	61	49
VFA (mg/L)	2,845	3,702	4,263	5,680
pH	7.1	6.98	6.93	6.88

promoting the reaction of dyes and fabric. However, when urea-based dyes are washed off, the urea decomposes quickly, releasing nitrogenous chemicals [42]. AnMBBR was acclimatized with low nitrogen concentration and high C : N (COD : Nitrogen) ratio in the feed (desizing) wastewater. Nitrogen in the feed increased with the increasing volume of reactive dye wastewater in feed. Nitrogen concentration in AnMBBR increased to 1,200 mg/L that reduced the COD : N ratio in AnMBBR below 350 : 5 due to decrease in influent COD and increase in ammonia nitrogen concentration in the dyeing wastewater and possible production of aromatic amines that lead to deterioration of the process performance. As reported earlier by Alepu et al. [40], ammonia concentration in anaerobic digestion between 50 to 200 mg/L appears to be beneficial to the process, whereas concentration between 200 to 1,000 mg/L has little impact on the performance of the anaerobic reactor. However, if the concentration rises to 1,000 mg/L there is a chance that inhibition will occur because this value is hazardous to the microbes of anaerobic digestion.

Data for additional parameters, analyzed immediately at steady-state before changing any conditions or increasing dye wastewater concentration in AnMBBR, are shown in Table 4. pH range, BOD$_5$ removal and methane content in the biogas were in the range of 6.88 to 7.1, 43 to 63% and 49 to 66%, respectively.

3. Projection of Pilot Plant Results to Full Scale Anaerobic Pretreatment Plant and Cost Estimation

3-1. Existing Activated Sludge Process without Anaerobic Pretreatment

The cost of the full scale anaerobic plant for pretreatment of textile desizing wastewater and potential payback period was assessed by the method reported by Baumann [43]. The current situation is further analyzed to determine the impact of a full scale anaerobic pretreatment plant on the subsequent aerobic activated sludge treatment process. The currently installed activated sludge process (ASP) is anticipated to have inlet COD concentration of 3 kg/m^3 and inlet wastewater flow of 2,280 m^3/d. The inlet COD load of ASP can thus be calculated as:

$$\text{COD Load}_{in,\ ASP} = 3\frac{\text{kg}}{\text{m}^3} \times 2{,}280\frac{\text{m}^3}{\text{day}} = 6{,}920\frac{\text{kg}}{\text{day}} \tag{1}$$

The COD load at outlet and COD load removed can be calculated through the outlet COD concentration of 0.14 kg/m^3:

$$\text{COD Load}_{out,\ ASP} = 0.14\frac{\text{kg}}{\text{m}^3} \times 2{,}280\frac{\text{m}^3}{\text{day}} \cong 320\frac{\text{kg}}{\text{day}} \tag{2}$$

$$\text{COD Load}_{removed,\ ASP} = 6{,}920\frac{\text{kg}}{\text{day}} - 320\frac{\text{kg}}{\text{day}} = 6{,}600\frac{\text{kg}}{\text{day}} \tag{3}$$

Under aerobic conditions, half of the removed organic compounds are used to build biomass, while the other half is converted into end products, mostly CO$_2$ and water. Therefore, the aerobic sludge production rate can be estimated as 3,300 kg/d. The local disposal cost per kg of solar dried sludge is 14 PKR (0.076 €) (considering the current rate of Euro (€) is 185 Pakistani rupee (PKR)). The total cost for sludge disposal is calculated as:

$$3{,}300\frac{\text{kg}}{\text{day}} \times 14\frac{\text{PKR}}{\text{kg}} = 46{,}200\frac{\text{PKR}}{\text{day}} \cong 16.9\frac{\text{million PKR}}{\text{Year}} = 91{,}351\frac{€}{\text{Year}} \tag{4}$$

According to the DWA [44], the oxygen demand for reduction of organic compound can be calculated by COD balance. Neglecting the COD bound in the biomass and various load cases for the aeration, the oxygen demand (6,600 kg-O$_2$/d) can be estimated equal to the removed COD load. Presuming a specific standard oxygen transfer rate (SSOTR) of 0.018 kg/(m^{3}N·m) [45] and using the depth of the current activated sludge tank of 5 m, the air flow rate can be calculated as:

$$\frac{6{,}600\frac{\text{kg}_{O_2}}{\text{day}}}{0.018 \times \frac{\text{kg}}{\text{m}^3\text{N}\cdot\text{m}} \times 5\ \text{m}} \times \frac{1\ \text{day}}{1{,}440\ \text{min}} = 51\frac{\text{m}^3}{\text{min}} \tag{5}$$

To estimate the potential cost savings due to an anaerobic pretreatment plant, the technical specifications of the currently applied aerators (Taiko Kikai Industries Co., Ltd.) are used to calculate the power consumption per air flow rate:

$$\frac{74.22\ \mathrm{kW}}{57.22\frac{\mathrm{m}^3}{\mathrm{min}}}=1.3\frac{\mathrm{kW}\cdot\mathrm{min}}{\mathrm{m}^3} \tag{6}$$

Using the air flow rate of 1.3 kW·min/m^3 and current rate of electricity of 17 PKR/kWh, the total electricity consumption and thus the cost for aeration can be calculated as follows:

$$1.3\frac{\mathrm{kW}\cdot\mathrm{min}}{\mathrm{m}^3}\times 51\frac{\mathrm{m}^3}{\mathrm{min}}\times 24\frac{\mathrm{h}}{\mathrm{day}}=1{,}585\frac{\mathrm{kWh}}{\mathrm{day}} \tag{7}$$

$$1{,}585\frac{\mathrm{kWh}}{\mathrm{day}}\times 17\frac{\mathrm{PKR}}{\mathrm{kWh}}=26{,}945\frac{\mathrm{PKR}}{\mathrm{day}}\cong 9.8\frac{\mathrm{million\ PKR}}{\mathrm{year}}=52{,}973\frac{€}{\mathrm{year}} \tag{8}$$

3-2. Assessment of Effects of Full Scale Anaerobic Reactor on Subsequent Aerobic Treatment Processes

The actual data from the pilot study is used for the cost calculations of full scale anaerobic moving bed biofilm reactor plant for pretreatment of desizing wastewater having COD concentration of 30 kg/m^3 and wastewater flow of 180 m^3/d. The approximate COD inlet load for a full scale anaerobic pretreatment plant is determined as:

$$\mathrm{COD\ Load}_{in,\ anaerobic}=30\frac{\mathrm{kg}}{\mathrm{m}^3}\times 180\frac{\mathrm{m}^3}{\mathrm{day}}=5{,}400\frac{\mathrm{kg}}{\mathrm{day}} \tag{9}$$

Expected COD load removed at optimum HRT of 6 days with 58% COD removal can be calculated as:

$$\mathrm{COD\ Load}_{removed,\ anaerobic}=0.58\times 5{,}400\frac{\mathrm{kg}}{\mathrm{day}}\cong 3{,}130\frac{\mathrm{kg}}{\mathrm{day}} \tag{10}$$

COD load and concentration other than desizing process at ASP are thus estimated as:

$$\mathrm{COD\ Load}_{in,\ other,\ ASP}=6{,}920\frac{\mathrm{kg}}{\mathrm{day}}-5{,}400\frac{\mathrm{kg}}{\mathrm{day}}=1{,}520\frac{\mathrm{kg}}{\mathrm{day}} \tag{11}$$

$$\mathrm{COD\ Concentration}_{in,\ other,\ ASP}=\frac{1{,}520\frac{\mathrm{kg}}{\mathrm{day}}}{(2{,}280-180)\frac{\mathrm{m}^3}{\mathrm{day}}}=0.72\frac{\mathrm{kg}}{\mathrm{m}^3} \tag{12}$$

Applying the experimental data of pilot scale study on the biogas conversion rate, the expected biogas and methane production from full scale anaerobic plant can be calculated as follows:

$$\mathrm{Bioas\ production}=0.30\frac{\mathrm{m}^3}{\mathrm{kg}}\times 3{,}132\frac{\mathrm{kg}}{\mathrm{day}}\cong 940\frac{\mathrm{m}^3}{\mathrm{day}} \tag{13}$$

$$\mathrm{Methane\ production}=0.22\frac{\mathrm{m}^3}{\mathrm{kg}}\times 3{,}132\frac{\mathrm{kg}}{\mathrm{day}}\cong 690\frac{\mathrm{m}^3}{\mathrm{day}} \tag{14}$$

The produced biogas can be used as a supplementary fuel with re-gasified liquefied natural gas (RLNG) in singeing, stenters and thermal oil boilers. If the biogas can be used as a supplementary fuel, the gas should be pretreated accordingly and some modification in the machinery may also be required. Detailed investigations on modifications of machinery to make them compatible for biogas fuel and cost estimations are required for gas pretreatment and its subsequent utilization as supplementary fuel. However, this aspect of the study is beyond the scope and therefore not investigated at present.

Using the lower calorific value of methane of 10 kWh/Nm^3 [46], the thermal energy of the produced biogas per day is calculated as follows:

$$690\frac{\mathrm{m}^3_{ch4}}{\mathrm{day}}\times 10\frac{\mathrm{kWh}}{\mathrm{Nm}^3}=6{,}900\frac{\mathrm{kWh}}{\mathrm{day}}=23.5\frac{\mathrm{mmbtu}}{\mathrm{day}} \tag{15}$$

According to Oil & Gas Regulatory Authority (OGRA) Pakistan, the current price for RLNG is 1,575 PKR/mmbtu. The financial benefits of the biogas would therefore amount to:

$$23.5\frac{\mathrm{mmbtu}}{\mathrm{day}}\times 1{,}575\frac{\mathrm{PKR}}{\mathrm{mmbtu}}\cong 37{,}013\frac{\mathrm{PKR}}{\mathrm{day}}$$
$$\cong 13.5\frac{\mathrm{million\ PKR}}{\mathrm{year}}=72{,}973\frac{€}{\mathrm{year}} \tag{16}$$

Under anaerobic conditions, only 5% of the removed organic compounds are transformed into biomass. The anaerobic sludge production can thus be estimated as 160 kg/d. As shown in the previous section, minimum 6 days of HRT for anaerobic reactor was found to be optimum. The optimal size for the full scale anaerobic plant for the flow of 180 m^3/d of desizing wastewater is estimated as:

$$\mathrm{Plant\ size}=6\ \mathrm{days}\times 180\frac{\mathrm{m}^3}{\mathrm{day}}\cong 1{,}100\ \mathrm{m}^3 \tag{17}$$

To estimate the costs and benefits of a full-scale plant as well as the potential payback period, the investment cost based on the quote provided by the local vendor, for anaerobic reactor of aforementioned volume capacity is estimated to be approximately 53 million PKR or 285,405 €. Electrical and mechanical equipment in Pakistan is largely imported while the civil works are usually conducted by local construction companies. Considering these facts, the investment costs are estimated to be 16.2 million PKR for civil works and 34 million PKR for electrical and mechanical equipment. According to the DWA [47] and Meyer [48], the yearly maintenance costs of an anaerobic wastewater pretreatment plant can be estimated as 1% of the investment in civil works and 2.5% of the investment in the mechanical and electrical equipment. The maintenance costs for a plant with an investment cost of 53 million PKR thus amount to:

$$\left(16.2\ \mathrm{mPKR}\times 0.01\frac{1}{\mathrm{year}}\right)+\left(34\ \mathrm{mPKR}\times 0.025\frac{1}{\mathrm{year}}\right)$$
$$=1.01\frac{\mathrm{million\ PKR}}{\mathrm{year}}=5{,}460\frac{€}{\mathrm{year}} \tag{18}$$

The costs for the electricity consumption of a proposed full scale anaerobic plant are estimated based on the figures for anaerobic plants at paper mills by DWA [47] as 0.01 €/kgCOD$_{removed}$ or 1.85 PKR/kgCOD$_{removed}$ amounting to:

$$0.01\frac{€}{\mathrm{kgCOD}_{removed}}\times 3{,}130\frac{\mathrm{kg}}{\mathrm{day}}\cong 31\frac{€}{\mathrm{day}}$$
$$=11{,}425\frac{€}{\mathrm{year}}=2.1\frac{\mathrm{million\ PKR}}{\mathrm{year}} \tag{19}$$

It is assumed that the operation and maintenance of the anaerobic plant can be conducted by one operator and one technician with a monthly estimated salary of 45,000 PKR and 30,000 PKR, respectively. The staff costs for the anaerobic plant are thus estimated at 75,000 PKR per month or 900,000 PKR per year (4,865 €/yr).

Based on the pilot study, a COD load removal of at least 3,130 kg/d can be estimated for a full-scale anaerobic plant. This means that the COD inlet load of the existing ASP would be reduced from 6,920 to about 3,790 kg/d. Considering the ideal conditions, it is assumed that the COD load reduction capacity (95%) of the existing aerobic ASP remains equal to the current state. It has to be stressed, that this case does not reflect the real conditions to be expected due to the presumably lower ratio of readily degradable organic matter in the reduced load to the ASP; the capacity of the ASP would most probably be lower than in this idealized case. Furthermore, the biological treatment is limited by nonbiodegradable [49] and inert compounds that contribute to the COD concentration in the wastewater [44].

$$\text{COD Load}_{in,\,ASP} = 1.66\frac{\text{kg}}{\text{m}^3} \times 2{,}280\frac{\text{m}^3}{\text{day}} = 3{,}785\frac{\text{kg}}{\text{day}} \tag{20}$$

$$\text{COD Load}_{out,\,ASP} = 3{,}785\frac{\text{kg}}{\text{day}} - \left(\frac{95}{100} \times 3{,}785\frac{\text{kg}}{\text{day}}\right) \cong 190\frac{\text{kg}}{\text{day}} \tag{21}$$

$$\text{COD Load}_{removed,\,ASP} = 3{,}785\frac{\text{kg}}{\text{day}} - 190\frac{\text{kg}}{\text{day}} \cong 3{,}600\frac{\text{kg}}{\text{day}} \tag{22}$$

The aerobic sludge production (50% of the removed organic compounds) thus can be estimated as 1,800 kg/d. The overall cost of aerobic and anaerobic sludge disposal can be calculated as:

$$\left(1{,}800\frac{\text{kg}}{\text{day}} + 160\frac{\text{kg}}{\text{day}}\right) \times 14\frac{\text{PKR}}{\text{kg}} \times 27{,}440\frac{\text{PKR}}{\text{day}} \cong 10\frac{\text{million PKR}}{\text{year}} = 54{,}054\frac{€}{\text{year}} \tag{23}$$

Oxygen demand of existing ASP with anaerobic pretreatment for the reduction of organic compounds can be assumed equal to the removed COD load (3,600 kg-O_2/d). The air flow rate thus can be calculated as:

$$\frac{3{,}600\dfrac{\text{kg}_{O_2}}{\text{day}}}{0.018\dfrac{\text{kg}}{\text{m}^3\text{N}\cdot\text{m}} \times 5\ \text{m}} \times \frac{1\ \text{day}}{1{,}440\ \text{min}} \cong 28\frac{\text{m}^3}{\text{min}} \tag{24}$$

The electricity consumption for air flow of 28 m^3/min and the cost for aeration can be calculated as follows:

$$1.3\frac{\text{kW}\cdot\text{min}}{\text{m}^3} \times 28\frac{\text{m}^3}{\text{min}} \times 24\frac{\text{h}}{\text{day}} \cong 874\frac{\text{kWh}}{\text{day}} \tag{25}$$

$$874\frac{\text{kWh}}{\text{day}} \times 17\frac{\text{PKR}}{\text{kWh}} = 14{,}858\frac{\text{PKR}}{\text{day}} \cong 5.4\frac{\text{million PKR}}{\text{year}} = 29{,}189\frac{€}{\text{year}} \tag{26}$$

Table 5 shows an overview of the costs and benefits of an anaerobic pretreatment for desizing wastewater. It also differentiates between the profit, i.e., the revenue generated from the biogas excluding the running costs of the plant and the monetary benefits which additionally include the cost savings from subsequent aerobic treatment. Therefore, the payback period of capital investment is approximately 927 days or 2.54 years. Thus, this study reveals that the anaerobic pretreatment of textile desizing wastewater appears to be economically feasible.

Table 5. Overview of the cost and befit analysis

Investment cost of anaerobic reactor	(million PKR)	(€)
Design engineering and construction supervision	2.6	14,054
Civil work	16.2	87,567
Electrical and mechanical equipment	34	183,784
Subtotal	52.8	285,405
Running cost of anaerobic reactor per year	(million PKR)	(€)
Maintenance of electrical and mechanical equipment	0.85	4,595
Maintenance of civil work	0.16	865
Electricity consumption	2.1	11,425
Staff salary	0.9	4,865
Subtotal	4.01	21,750
Revenue per year	(million PKR)	(€)
Biogas production	13.5	72,973
Cost saving from subsequent aerobic treatment	(million PKR)	(€)
Aeration cost	4.4	23,784
Sludge disposal cost	6.9	37,297
Subtotal	11.3	61,081
Total monetary benefits	20.79	112,304
Payback period (year)	2.54	

CONCLUSIONS

An anaerobic moving bed biofilm reactor (AnMBBR) was found to be proficient for COD and BOD_5 removal and biogas production from textile desizing wastewater. Increasing OLR from 1±0.05 to 4.9±0.43 kgCOD/m^3/d or reducing the HRT from 32 to 6 days resulted in enhanced biogas production. Removal of COD and BOD_5 at optimum OLR (4.9±0.43 kgCOD/m^3/d) was 58 and 65%, respectively. The performance of AnMBBR in terms of COD, BOD_5 and color removals and biogas production deteriorated as the concentration of reactive dyes in the feed increased. Cost estimation of anaerobic digestion of textile desizing wastewater indicated a net profit of 21.09 million PKR/yr or 114,000 €/yr and potential payback period of 2.54 years. These results suggest that anaerobic pretreatment of textile desizing wastewater appears to be a promising technology for its full-scale implementation.

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