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High strength municipal wastewater treatment using a jet loop anaerobic bioreactor with external cross flow membrane filtration (JLAMBR)

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ABSTRACT

This study investigated whether or not the complete treatment of high strength municipal wastewater of arid countries through a jet loop anaerobic membrane bioreactor is possible, and whether the treatment could make the wastewater as well as its ingredients available for further material recycling or energy recovery. The experiment was conduct with glucose-based wastewater of 400–600 mg DOC/L (1,000–1,500 mg COD/L). The results of the experiment showed that the effluent concentration of the system was always below 30 mg DOC (75 mg COD/L and 60 mg BOD/L)/L (the total degradation efficiency of 95%) at the steady state and an average biogas of 0.42 m^3/kg $COD_{eliminated}$ could be produced. So it was found that organic ingredients of municipal wastewater in arid countries dose not solely present pollutants to be treated, but can serve as a resource. But the performance of the membrane filtration fell short of expectations because of the high portion of the finest particle (90% of sludge particle (X_{90}) < 5.2 μm).

Keywords: High strength municipal wastewater treatment; Jet loop anaerobic bioreactor; External cross flow membrane filtration

1. Introduction

For the treatment of low strength wastewater flows from industry and households, aerobic processes (activated sludge process) are the prior art. They have been well-introduced, are widespread, cost-effective, and meet the requirements relating to the required effluent quality [1]. But to a large extent, these do not perform material recycling or use of wastewater constituents or components supplied to them. They produce oxidation residue in the form of biomass, whose elimination requires other expenses. On the other hand, anaerobic wastewater treatment processes, whose biomass production is much less [2,3] and whose efficiency through the production of biogas is unequally larger, lack applicability in the treatment of low-strength wastewater stream due to process-related difficulties and limitations.

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Thanks to the great progress in the development and production of durable and more cost-effective membranes and modules due to the commercialization of aerobic membrane bioreactor (MBR) technology, anaerobic MBR (AMBR) research activities have been further intensified since the early 90s are ongoing. Its benefits are particularly evident in the treatment of highly concentrated industrial wastewater. It is often used as a pretreatment step of highly concentrated wastewater (COD > 2,000 mg/L) [4]. Investigations into membrane fouling and scaling, membrane cleaning and surface layer management [5–11] have also been performed as the test of new membrane materials [12,13] or the application of submerged membranes [14–17] in the anaerobic wastewater technology. Recently, there has been a movement to start treating domestic wastewater with the AMBR technology and the first publications about it [17–21].

The domestic wastewater is generally low-strength wastewater (around 500 mg COD/L). But chemical oxygen demand (COD) concentration of undiluted domestic wastewater in arid countries ranges from 1,250 to 1,500 mg/L (1,000–1,200 mg BOD/L). Therefore, this can correspond to high strength municipal wastewater compared with low-strength domestic wastewater and more biogas can be obtained from it than low-strength domestic wastewater.

Municipal wastewater itself of arid countries contains materials (carbohydrates) which inherently are high-energy compounds. Chemical energy extracted from municipal wastewater carbohydrates has the great potential as a renewable energy. This energy is produced through the contaminant removal in anaerobic treatment of municipal wastewater. The AMBR system is leading to a rejection of the organic matter in the reactor resulting in an increased pollutant concentration so that anaerobic systems become efficient and economic even for municipal wastewater. Furthermore, under anaerobic conditions, it is possible to hydrolyze and degrade substrates which are not degradable in an aerobic environment [22]. The comparably high biomass concentration of MBR is resulting in high volumetric yields and therefore, smaller reactor volume. It holds a great promise of transforming municipal wastewater treatment facilities into green energy generating plants.

This work aimed to find a way to take advantage of the value-added potential of high-strength municipal wastewater in arid countries. The procedural approach to this was to investigate the full treatment of their municipal wastewater in a single step using a jet loop AMBR (JLAMBR) and in addition biogas production as a renewable resource of energy. The floc size of anaerobic activated sludge in JLAMBR/cross flow filtration (CF)-system was also compared with that of aerobic activated sludge in municipal wastewater treatment plant because the former could be destroyed by the high energy and the associated extreme shear forces in JLAMBR/CF-system.

2. Materials and methods

2.1. Experimental apparatus and operation

Fig. 1 shows the schematic diagram of the apparatus that was employed for the experiments. The reactor consists of a cylindrical reaction chamber (1) with a diameter of 250 mm and a height of 1,300 mm, and a gas headspace (2) with 450 mm diameter and 500 mm height above the liquid volume. In the center of the reaction chamber, a round tube with a diameter of 150 mm and a length of 1,000 mm is arranged. The reactor has a cylindrical degassing head of 450 mm diameter and 500 mm height at the upper end. The level of liquid in the reaction space is set with a height-adjustable permeate over flow vessel, so that the volume is 0.05 m^3.

The outer wall of the reactor is covered with glass wool and a fabric woven with the glass fiber for the thermal insulation, and the liquid in the reactor is heated over a Kyrosat (Haake T, Germany) for temperature control, and is also arranged at the inlet stream. At the bottom of the reactor, a centrifugal pump sucks the activated sludge mixture and delivers it through a membrane module (4), and then, it is returned into the reactor from the top through a nozzle. The momentum of the liquid jet creates a flow loop around the circulation tube attached in the center of the reactor vessel. Through the use of the flow loop in combination with the nozzle, good mixing and high

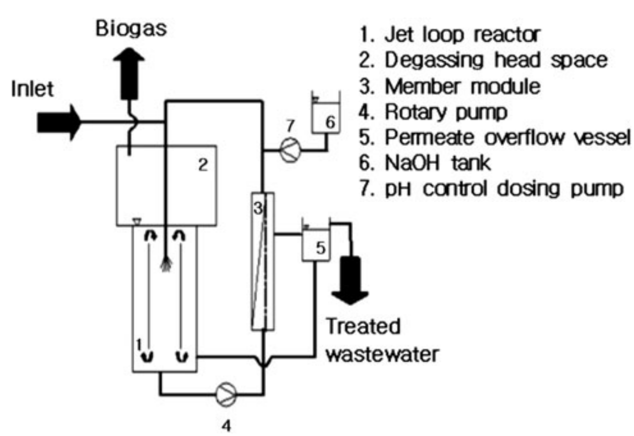

Fig. 1. Schematic of the jet loop anaerobic bioreactor combined with a cross flow membrane filtration.

mass transfer can be ensured. The feed is supplied to the circulation flow over an eccentric screw pump and displayed by means of an inductive flow meter (Krohne, Germany). The permeate separated in the membrane module reaches a height-adjustable collecting vessel, which holds the liquid level in the reactor constant. In this way, only the permeate volume leaves the reactor system as outlet and it is completed by the inlet. The biogas leaves the reactor after the liquid/gas separation at the top, where a lighter system overpressure can be adjusted over a needle valve to avoid pressure fluctuations in the system. A drum gas meter is used for the determination of the biogas flow and a Dulcometer (Prominent, Germany) is used to control the pH in the reactor. As needed, NaOH or HCl from the storage tank is dosed into the reactor recycle line.

The membrane unit employed for the solid retention consisted of a pipe bundle membrane module, which was assembled with 7 parallel-arranged tubular membranes with hydraulic diameters of 14.4 mm and a length of 1.8 m. The installed membrane surface was 0.57 m^2. The membrane material (WFS 0120, X-Flow (formerly Stork, Netherlands)) used in the module (Stork 7PR (Netherlands)) was a composite ultrafiltration membrane (polyacrylnitrile on polyester carrier) with a molecular weight cut-off of ca. 150,000 Dalton.

2.2. Experiments

Degradation tests were conducted with synthetic wastewater, which was prepared by the addition of the substances in tap water. Major carbon was sucrose and the final dissolved organic carbon (DOC) concentration was 500–600 mg/L (1,250–1,500 mg COD/L and 1,000–1,200 mg BOD/L). This corresponds to an average DOC concentration of municipal wastewater in arid countries. The composition of the synthetic wastewater is presented in Table 1. The storage tank was cleaned every second until the third day, and the wastewater was prepared with tap water to reduce acidification.

Table 1
Composition of synthetic wastewater

Substance	Concentration (mg/L)
Sucrose	1,600
Ammonium chloride	17.4
Urea	3.5
Calcium chloride	0.6
Magnesium sulfate 7 hydrate	3.5
Natrium sulfate	1.7
Dikalium hydrogen phosphate	5.2
Kalium dihydrogen phosphate	1.7

Sludge from an anaerobic digester of a municipal sewage treatment plant was used as inoculums of the anaerobic reactor. The addition of the synthetic wastewater was started with a feed flow rate of 1 L/h, and this rate was increased continuously until the maximum permeate capacity of the plant was reached. The pH value in the reactor was kept constant at pH 7.1. The reactor temperature was adjusted to remain constant at 37.5°C. The anaerobic reactor was initially operated with total solids (TS) concentration of ca. 7.5 g/L. In order to maximize the reactor loading rate, the removal of the surplus sludge was omitted in the first test phase (ca. 150 days). In the course of the investigations, the TS concentration was maintained constant according to the defined amount of sludge removal.

At regular intervals, the inlet, the outlet and the liquid of the reactor were sampled. The DOC, the COD, the biological oxygen demand in 5 days (BOD_5) and the TS content of the samples were analyzed.

2.3. Analytical methods

DOC concentration was analyzed using TOC-Analyzer TOC-5000 (Shimadzu, Kyoto, Japan) according to DIN 38409-3 [23]. The TS, COD and BOD_5 concentrations were analyzed according to DIN 38414-2 [24], DIN 38409-1 [25] and DIN 38409-51 [26], respectively. The viscosity of the activated sludge suspension was measured using the RV 2 rotation viscosity-meter (Haake, Germany) and biomass size was measured with the Helos laser diffraction analyzer (H0613) (Sympatec, Germany).

3. Results and discussion

3.1. Treatment efficiency of the system

Figs. 2–6 show the variations in the major parameters for the experimental period at the test plant. During startup of the plant, the COD loading rate was increased from 1 to 4 kg COD/m^3 d after an adaptation period of 30 days, and up to 5 kg COD/m^3 d in the continued operation. Thus, the reactor reached a BOD loading rate of 4 kg BOD/m^3 d, and correspondingly, a BOD sludge load of 0.2 kg BOD/kg TS·d, which was reached after 200 working days and kept at a constant rate during subsequent operation.

As expected, the gas was only produced after the adaptation of microorganisms to the synthetic wastewater. As part of the growth of biomass from 7.5 to

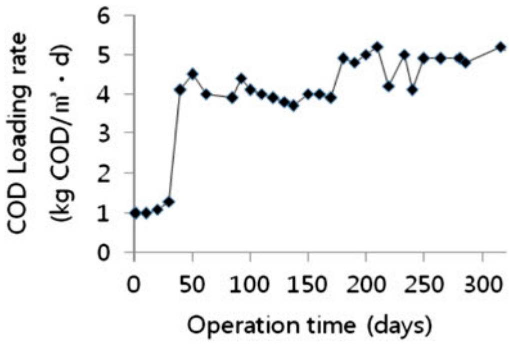

Fig. 2. Variation of COD loading rate.

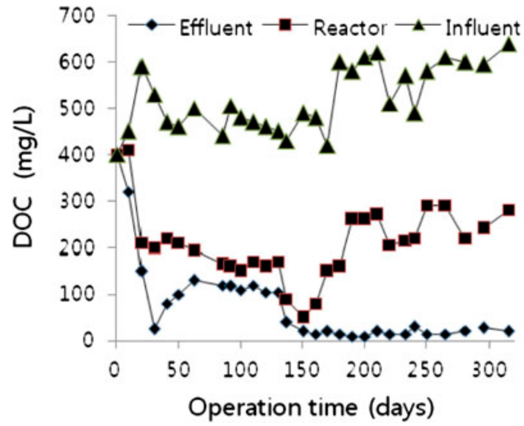

Fig. 4. Variation of DOC concentration.

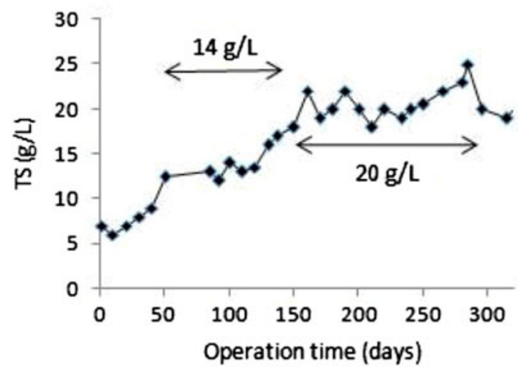

Fig. 5. Variation of TS concentration.

20 g TS/L and the associated adaptation of the microbial populations of microorganisms to the substrate conditions, the biogas production reached a first plateau at 40 L/d, due primarily to the fact that a portion of the dissolved carbon left again the system through the effluent without being degraded (Figs. 3 and 5). Maximum biogas production of approximately 100 L/d was measured only after decoupling the hydraulic retention time from the DOC concentration in the reactor (see Figs. 2 and 4). This is supported by decreasing the effluent DOC concentration with the simultaneous increase of the DOC concentration within the reactor. Its maximum of 100 L/d corresponds to a specific biogas production of 0.42 m^3/kg $COD_{eliminated}$, which can be considered as an average for the treated substrate [27].

The DOC concentration in the effluent at the beginning of the experiments reached values by 100 mg/L (250 mg COD/L and 200 mg BOD/L. Further purification was not possible in this experimental phase, since the 12.5 h residence of the wastewater in the reactor system at this time provides for a discharge of COD from the reactor. From the 150th operation day, the effluent concentration decreased to values that were consistently below 30 mg DOC/L (75 mg COD/L and 60 mg BOD/L). This could be due to the fact that the population of the microorganisms was, on the one hand, adapted to the conditions prevailing in the reactor. After the increase in the fast-growing acidifying microorganisms at the beginning of operation and their production of the intermediate as substrate for the slower-growing acetogenic and methane generating bacteria arts, they have adapted to the selection pressure, and then, the population adapted to the substrate supply because of available time and high substrate supply.

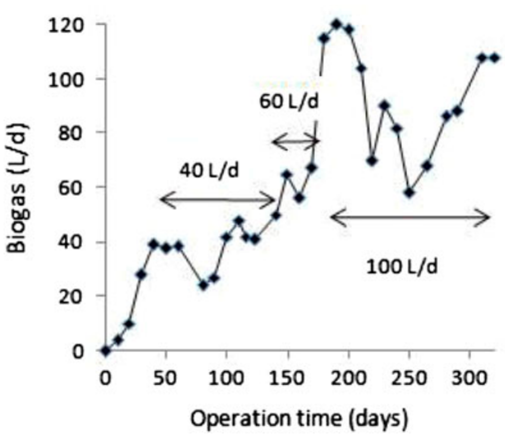

Fig. 3. Variation of biogas generation.

Through coupling with the membrane filtration, there was also the possibility of increasing the total substance concentration in operation through the retention of the biomasses, and thus of improving the substrate loading rate and the discharge values. The stagnation often described in other studies, or even a decrease in biomasses in the system through hydrolysis or through depositing on the membrane surface by

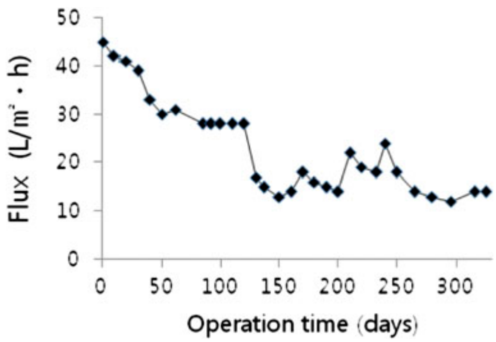

Fig. 6. Variation of flux.

coupling with a membrane separation step, as Choo and Lee [5] suggested, was not observed.

Surface layer (bio-film) forming in continuous operation also provided a further improvement of the discharge values. To accomplish this, on the one hand, biomass was attached to the membrane, similar to a fixed bed. It works through the permanent transport of nutrients to the lowest layers as a much more biologically active and effective bio-film, and deprives the convectively transported wastewater of nutrients. On the other hand, it forms a bio-film that is often called as secondary membrane due to its compact structure and bearing appearance like gel, which is an additional barrier due to a strong network through extra-cellular polymeric substances [28]. This is another resistance against the mass transport, which exceeds the transport resistance of the membrane itself many times in the case of the MBR.

The effectiveness of this "secondary membrane" for the retention of the dissolved carbon compounds can be recognized as very good through the increase in DOC concentration in the reactor from 50 to 250 mg/L after 150 days of operation in Fig. 4. While the degradation of the dissolved carbon compounds by the bio-film on the membrane alone leads to a reduction of the effluent concentration, an increase in DOC in the reactor can be only ascribed to an active retention.

Since the kinetics of specially acetogenesis and methanogensis is distinguished by comparatively large Monod-Constants (K_s), which indicate a low substrate specificity, the concentration enables the overcoming of a kinetic problem, which then always exists, when low effluent values are kept at a low substrate affinity (high K_s value) without to enhance the retention time and thus the reactor volume. The principle of the classical completely mixed reactor, where the reactor concentration is equal to the effluent concentration, is here no longer available to be used, and the reaction volume may be used more effectively.

Despite a further increase of the loading rate to 5 kg COD/m^3 d and a reduction in the hydraulic retention time to 8 h, effluent values below 30 mg DOC/L were observed from 150th day of operation, which corresponds with a total degradation ratio of 95%.

3.2. Performance of membrane unit

Also in Figs. 5 and 6, the TS concentration and flux are shown over the lifetime of the test plant. It was found at the beginning of the procedure that the expected flux from the preliminary tests could not be achieved. At a flow velocity of 2.5 m/s and a transmembrane pressure of 2.8 bar, flux value of only 20 L/m^2 h was measured. Because the TS concentration in the reactor was increased to 20 g/L during the starting phase, the flux fell to 12 L/m^2 h up to the 150th day of operation. To investigate the effects of the membrane materials on the flux, the membranes from polysulfone were replaced by polyvinyliden fluoride-membranes (asymmetrical ultrafiltration membrane in composite construction, polyester/polysulfone carrier, nominal cut-off 25 nm) after the 120th day of operation. This led again only to a short-term increase of flux.

One reason for the low flux values is the flow conditions in the membrane tubes. Membrane processes for biomass separation are in the bio-film controlled operating range, so the efficiency of the membrane decreases rapidly with increasing biomass content, since this continues to increase the bio-film thickness and thus the filtration resistance is increased. Similarly, the dynamic viscosity of the activated sludge

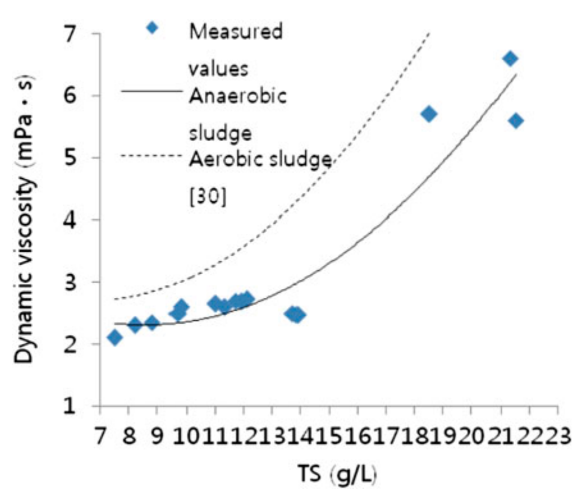

Fig. 7. Dynamic viscosity of activated sludge as function of the MLSS concentration.

suspension increases with increased solids content (see Fig. 7).

The viscosity, however, is related to both the membrane flux and the Reynolds number, and thus is inversely proportional to the turbulence. It affects the flux performance greatly. Nevertheless, the viscosity measured in the test plant is less than the viscosity of aerobic MBR s in operation [29]. A closer look revealed, however, an enormous proportion of finer and finest particles, as can be seen in the distribution density function of volume equivalent spheres of the activated sludge from anaerobic CF-system in Fig. 8. The floc structure of the anaerobic activated sludge was destroyed by the high energy and the associated extreme shear forces, and microorganisms were only very small agglomerates (<10 μm) or were present as single bacteria (<2 μm) in the suspension. Activated sludge of a municipal aerobic wastewater has much wider and larger average particle sizes than those of AMBR/CF (anaerobic MBR with cross flow filtration) (see Fig. 8). This unexpectedly high portion of the finest particle (90% of sludge particle (X_{90}) < 5.2 μm) in the AMBR/CF could make the activated sludge separation very uneconomical and ineffective in the final clarifier because anaerobic bio-solids exhibit poor settle-ability due to their diffusible and somewhat filamentous nature [5]. The size reduction of the mixed liquor bio-solids [31] or the size distribution of particles being filtered [32] proved to reduce membrane permeability.

It should be recognized that the floc structure of anaerobic sludge tolerates high shear forces far less

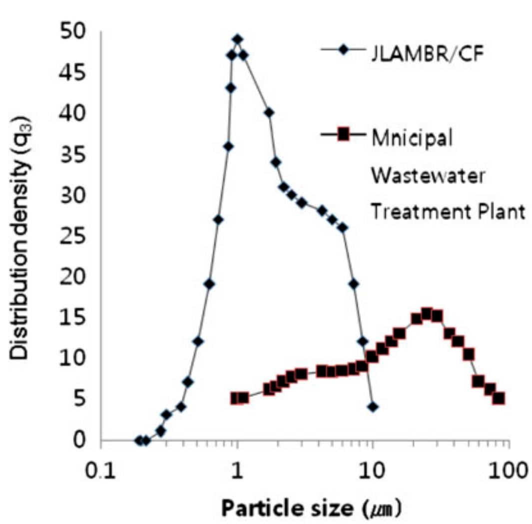

Fig. 8. Distribution density function of volume equivalent sphere for activated sludge from the anaerobic MBR with cross flow filtration (JLAMBR/CF) and the activated sludge of a municipal wastewater treatment plant.

well than the floc structure of aerobic sludge. It keeps some minimum floc sizes in a comparable energy input, as shown in Table 2, which provides a comparison of the median values (X_{50}) of the distribution density functions of various activated sludge, and therefore, also has advantages for membrane filtration.

Since the membrane system was in the bio-film controlled operating range and the membrane module had small loss of pressure (0.2 bar at the flow velocity = 2.4 m/s and the flux value of 19.2 L/m^{2}h) compared with a membrane system installed on an industrial scale, from the 227th day of operation, the operating pressure of the circulation pump was lowered so that the transmembrane pressure fell from 2.8 to 1.8 bar. This did not adversely influence the flux, but did reduce the energy input by 35%.

A chemical cleaning of the membrane on the 170th day of operation according to the cleaning procedure of membrane done by Seo and Vogelphol [34] could raise permeate capacity only for a short time, and therefore, periodic cleaning at an interval of 5–10 days was required in order to maintain the flux at 20 L/m^{2}h. The exchange of membrane material on the 210th and 240th day of operation using a different type of membrane (X-Flow WFF × 0281 of the company X-Flow (formerly Stork, Netherlands)), also brought no sustained improvement of the permeate flow, so it must be assumed that the low flux cannot be significantly improved by design alone, or by membrane-side interventions in the reactor system.

From the above results, in order to improve the low flux in this filtration concept and limit the effect of the floc breakdown on the flux, the single-stage JLAMBR could be supplemented with an acidification step for modifying the process into two-stage

Table 2
Median values of particle size distribution density of different activated sludge

Operation manner	X_{50} (μm)	Reference
Aerobic (municipal wastewater treatment plant)	40–65	*
Aerobic (HCR)	14–25	[33]
Aerobic (IJR/UF)	5–15	[30]
Anaerobic (JLAMBR/CF)	1.5	*
Anaerobic (JLAMBR/SM)	1–14	*

Notes: HCR: high-performance compact reactor, IJR: impinging jet reactor with ultra filtration membrane, JLAMBR/SM: jet loop anaerobic bioreactor with submersed membrane filtration, and *: self-measurement.

JLAMBR and an intermediate clarifier could be placed between the acidification step and the methane fermentation step. Aim of this action is that the solid substrate concentration in the JLAMBR could be reduced through separation of hydrolyzing and acidifying phase from the acetogens and methanogens in order to avoid the limit of the flux performance through the high biomass concentration in the system. On the other hand, the treatment capacity of the entire system should be raised through the enhancement of particularly the very slow growing methane bacteria under support of the membrane without competition with the acidifying bacteria because the methanogens in this case can be considered as the rate-limiting step for the entire reaction cascade. Another alternative filtration concept for preventing the destruction of flocs could be the JLAMBR with submersed membrane filtration.

4. Conclusions

High strength municipal wastewater of arid countries was treated using a jet loop anaerobic bioreactor with cross flow membrane filtration. The coupling of an anaerobic reactor with a membrane separation stage proved to be effective. In addition to the expected complete biomass retention and the completely solid-free effluents, the DOC concentration in the reactor could be decoupled from the hydraulic residence time of the wastewater. The resulting kinetic advantages benefited the degradation of organic wastewater contaminant at low feed concentration. The effluent concentration of the system was consistently under 30 mg DOC/L (the degradation efficiency 95%). Trouble-free static operation with a hydraulic retention time of 8 h and a loading rate of 5 kg COD/m^3d could be maintained. Despite high volumetric wastewater flow rate, an average biogas production of 0.42 m^3/kg $COD_{eliminated}$ resulted in no loss biogas with the effluent. This indicates the very good substrate transport characteristics of the reactor system. The dynamic viscosity and the particle size measured in the AMBR/CF were less than those of aerobic MBRs in operation. The performance of the membrane filtration, therefore, fell short of expectations. In static operation, a flux of merely 15 L/m^2h (transmembrane pressure = 1.8 bar and flow velocity = 1.5 m/s) could be obtained.

Acknowledgments

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