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Organic matter and nitrogen removal in a hybrid upflow anaerobic sludge blanket—Moving bed biofilm and rope bed biofilm reactor

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ABSTRACT

A novel hybrid upflow anaerobic sludge blanket—moving bed biofilm reactor followed by rope bed biofilm reactor (UASB-MBBR-RBBR) was designed and operated for about a year to achieve removal of organic matter and nitrogen from sewage. The hybrid reactor could achieve chemical oxygen demand (COD) removal of 99 ± 1% with an effluent COD concentration of around 7 ± 3 mg/L at an organic loading rate (OLR) of 2 kg COD/m^3 day and a total nitrogen removal of 89 ± 8% by combination of nitrification-denitrification processes at a nitrogen loading rate of 0.2 kg TN/m^3 day. Innovative reactor design with moving rope bed supporting oxic and anoxic microenvironments favoured high nitrogen removal rate. The major problem of sludge washout in UASB reactor could be eliminated by the use of moving media in the UASB-MBBR. A maximum biogas production of 0.61 m^3/kg COD removed could be achieved at an OLR of 2 kg COD/m^3 day. The hybrid UASB-MBBR-RBBR technology could thus provide an alternative, low maintenance, economical and efficient system for simultaneous carbon and nitrogen removal and energy recovery, which is not otherwise possible using conventional secondary sewage treatment processes.

1. Introduction

Different treatment technologies used in India can be classified into natural system (Oxidation pond, Waste stabilization pond, Aerated lagoon, Kernel technology), conventional system (Activated sludge process, Trickling filter), modified system (Extended aeration), advanced technologies (Sequencing batch reactor, Biofar, Moving bed biofilm reactor (MBBR), Submerged aerobic filter, and Upflow anaerobic sludge blanket (UASB) reactor). Conventional sewage treatment processes involve high capital, maintenance and operational cost, huge energy requirements, which makes them unsuitable for use in developing countries [20]. Energy efficient low-cost waste treatment systems are the best choice for such countries. Anaerobic treatment systems excel in such respect. The traditional anaerobic processes are septic tanks or imhoff tanks, anaerobic pond, anaerobic filter, expanded bed reactor, and UASB reactor. Removal efficiency of septic tanks or imhoff tanks are very low and require a higher retention time to achieve desired efficiency and further demanding proper effluent disposal facility, thus rendering the technologies unattractive. Anaerobic ponds though efficient in organic matter removal occupy huge land area. Anaerobic filter faces operational problems due to blockage. Fluidized bed reactor requires additional pumping to keep the media in expansion [22].

UASB reactors are the most widely used high rate anaerobic wastewater treatment process and several full scale reactors have been operated world-wide [8,13]. Most of the successful applications of UASB reactors are to treat high strength industrial wastewaters [13]. Municipal sewage treatment using UASB reactors is restricted to tropical regions where temperature of the raw sewage allows fast hydrolysis of suspended organic solids [25].

Sato et al. [20] evaluated the treatment efficiency of sixteen UASB reactor based sewage treatment plants on the Yamuna river basin in India and observed that none of the plants met the discharge standards for biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS) or nutrients as total Kjeldahl nitrogen (TKN). The surface water discharge standards for BOD, COD, SS and TKN in India are 30 mg/L, 250 mg/L, 100 mg/L and 100 mg/L, respectively [11]. Considering these reports, the major problems with UASB reactor can be assumed to be sludge washout and improper mixing due to a low upflow-velocity and biogas production at low organic loading rates (OLRs)

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applicable during sewage treatment. UASB reactors have been observed to give poor performance at low OLRs, due to improper mixing because of low biogas production rate, and the effluent often do not meet discharge standards [13]. To solve these problems related to UASB reactor operation, researchers have started to use hybrid reactors by coupling the UASB reactor with some other treatment technology such as membrane bioreactor (MBR) [8,19], aerated bio-filter (ABF) [9], sequencing batch reactor (SBR) [14], activated sludge process (ASP) [15], trickling filter (TF) [18], down-flow hanging system (DHS) [21] etc.

Using moving media in the UASB reactor, operated at lower OLR, might help to solve the problem of mixing and sludge washout. Even after improving organic matter removal efficiency, being anaerobic process the nutrient removal capability of UASB reactor is poor. To remove excess nitrogen from the effluent of UASB reactor, it is required to incorporate processes that ensure efficient nitrogen (N) removal, primarily involving the elimination of ammonium-nitrogen (NH_4^+-N) and a reduction in nitrate-nitrogen (NO_3^--N). If a simultaneous reduction in NH_4^+-N and NO_3^--N is to be achieved, establishment of suitable conditions to facilitate both nitrification and denitrification is necessary. This represents a challenge to engineers while designing wastewater treatment systems, because these two processes are catalysed by physiologically distinct groups of micro-organisms i.e., autotrophic nitrifiers and majorly heterotrophic denitrifiers, which have fundamentally different metabolic requirements [10]. High rates of simultaneous nitrification and denitrification can be achieved, in biofilm type systems where both oxic and anoxic micro-environment is present [10]. Nitrification can occur at the liquid/biomass interface, while denitrification of nitrate (or nitrite) may be found in deeper sub-surface biomass zones [10]. Combined carbonaceous oxidation, nitrification and denitrification systems however can require frequent and costly maintenance since slight imbalance in pH, alkalinity will cause detrimental effects on performance [10].

In this study a novel hybrid reactor consisting of upflow anaerobic sludge blanket—moving bed biofilm reactor and rope bed biofilm reactor (UASB-MBBR-RBBR) was designed and monitored for its ability to remove organic carbon and nitrogen from a synthetic wastewater having similar strength as of sewage. Nitrogen and organic matter mass balance was investigated. This approach can provide data and methodology that can be used by engineers and scientists to design and operate these types of hybrid systems and optimise organic matter and nitrogen removal efficiency.

2. Materials and methods

2.1. Design and operation

The hybrid reactor was fabricated using a 5 mm thick Plexiglass cylinder having 100 mm internal diameter. It comprised of a 2.1 m high column housing the UASB-MBBR with a liquid depth of 1.9 m, followed by a 1.4 m high column housing the RBB reactor. The gas liquid solid separator is located at the depth of 0.3 from the top of the reactor. Commercially used Polypropelene media in MBBR with specific surface area of 400 m^2/m^3 and of volume 5 L, that is 1/3rd of the effective working volume, was added in UASB reactor to enhance sludge retention. Nylon ropes of projected surface area of 0.38 m^2 were used as media in the RBBR (Fig. 1).

Synthetic wastewater [6] having a COD of about 500 mg/L with sucrose as carbon source and total nitrogen (TN) of about 50 mg/L was pumped continuously from a feed tank using a peristaltic pump (Miclins, India) through two inlet tubes of 8 mm internal diameter into the UASB-MBBR. The synthetic wastewater also contained (per gram of COD) $NaHCO_3$, 1500 mg; NH_4Cl, 318 mg; $CaCl_2 \cdot 2H_2O$, 250 mg; $MgSO_4 \cdot 7H_2O$, 64 mg; K_2HPO_4, 27 mg; and

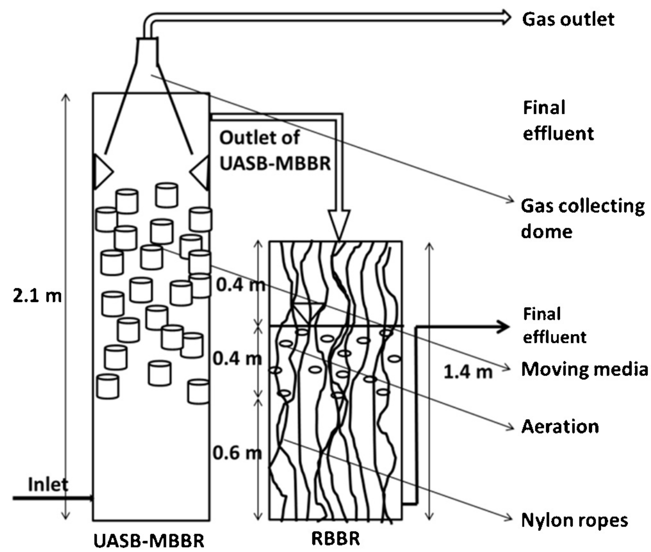

Fig. 1. Schematic diagram of the laboratory setup.

KH_2PO_4, 9 mg. Trace metals were added as $FeSO_4 \cdot 6H_2O$, 10.00 mg l^{-1}; $MnSO_4$, 0.526 mg l^{-1}; $ZnSO_4 \cdot 7H_2O$, 0.106 mg l^{-1}; H_3BO_3, 0.106 mg l^{-1}; and $CuSO_4 \cdot 5H_2O$, 4.5 $\mu g\, l^{-1}$, $CoCl_2$, 105.2 $\mu g\, l^{-1}$, $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$, 105.2 $\mu g\, l^{-1}$. For a duration of 15 days, the reactor was also operated on raw sewage collected from sump of Pump House of IIT Kharagpur campus at an OLR of 1.5 kg COD/m^3 day. Since, the raw sewage had a COD of only 200 ± 81 mg/L, it was spiked with sucrose to have an average COD concentration of 500 mg/L.

To avoid short-circuiting of the influent from sludge bed in the UASB reactor and existence of dead pocket at the bottom of the reactor, the inlet end was kept open towards bottom of the reactor, so that the feed should first strike at the bottom and get evenly distributed over the entire cross-sectional area of the reactor. Effluent of the UASB-MBBR was fed into the RBBR. Out of total height of 1.3 m of RBBR, top 0.3 m media was not submerged and allowed the effluent of UASB reactor to trickle down over the ropes, exposed to natural air. Out of remaining 1 m submerged depth of the media, the top 0.4 m was aerated using aqua-pumps to support nitrification and the bottom 0.6 m was intended to be under anoxic conditions to facilitate denitrification. Effluent was leaving the RBBR from bottom, maintaining a liquid height of 1 m in the reactor. The hybrid UASB-MBBR was operated under seven different OLRs as given in Table 1. The UASB-MBBR was inoculated with 5 L of anaerobic sludge with VSS of 23.5 g/L collected from bottom of a septic tank located in IIT Kharagpur campus, where the entire wastewater of the campus is collected, and it was operated continuously for 280 days with 40 days of operation under each OLR. No sludge addition was done in the RBBR. Spontaneous growth of bacteria was observed in the RBBR as response to the outlet of the UASB-MBBR.

2.2. Sampling and analysis

In order to assess COD reduction profile over height, the reactors were equipped with sampling ports. Parameters like COD, NH_4^+-N, TKN, volatile fatty acids (VFA), alkalinity, volatile solids (VS), total solids (TS), volatile suspended solids (VSS), and total suspended solids (TSS) of the influent, effluent and within the reactor were measured as per the Standard Methods [2]. Total dissolved solids (TDS), pH and NO_3^--N were measured using electrodes (Thermo, USA). Turbidity was measured by Systronics Turbidity Meter. Extracellular polymeric substances (EPS)