Physical Characteristics and Removal Performance of Aerobic Granular Sludge in Biological Treatment of Domestic Wastewater

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Abstract. This study aims to demonstrate the formation of aerobic granular sludge (AGS) for domestic wastewater treatment applications in hot climate and low humidity conditions (e.g. Saudi Arabia) as well as to characterize and examine the bioreactor performance in removing organic matter and nutrients. Based on the study, aerobic granular sludge (seeded with domestic activated sludge from Al-Madina Wastewater Treatment Plant and fed with synthetic wastewater with an organic loading rate (OLR) of 1.6 kg COD $m^{-3}d^{-1}$) was successfully cultivated with average size ranging from 1 to 2 mm in a laboratory scale sequencing batch reactor (SBR) system operated at 30 days with a complete cycle time of 3 h and at the working temperature of 30 ± 1°C. Results also showed that the aerobic granular sludge formed had excellent settling ability (settling velocity, 38.98 mh^{-1} and MLSS, 7.8 gL^{-1}) and great removal performance of COD and nutrient (i.e. more than 90%).

1. Introduction

Biological processes are a cost-effective and environmentally sound alternative to the chemical treatment of wastewaters. The biological process based upon suspended biomass (i.e., Activated sludge processes) is effective for organic carbon and nutrient removal in municipal and industrial wastewater plants (Borkar et al., 2013). Recently, interesting alternatives for the conventional activated sludge systems were developed relying on compact and self-immobilized granulated biomass. Examples are for instance Aerobic Granular Sludge (AGS), Sequenced Batch Reactor (SBR), Upflow Anaerobic Sludge Bed (UASB), as well as Expanded Granular Sludge Bed technology (EGSB) (Beun et al., 1999; Lettinga and Hulshoff Pol, 1991; Morgenroth et al., 1997; Rinzema et al., 1993). Aerobic granulation in SBRs has been reported by many researchers and is widely used in treating high-strength wastewaters containing organics, N and P, and toxic substances as the SBR operation conditions (cyclic feeding and starvation, high shear stress and short settling time) promote development of granules (Morgenroth et al., 1997; Beun et al., 1999; Peng et al., 1999; Etterer and Wilderer, 2001; Tay et al., 2001a; Liu and Tay, 2002, Adav et al., 2008b; Adav et al., 2009d).

Aerobic granular sludge process has been proposed as a promising approach to biological wastewater treatment (de Kreuk et al., 2007). Compared with conventional bioflocs, aerobic granular sludge has dense microbial structure, good settling ability, high biomass retention and the ability to withstand a high organic loading rate (Morgenroth et al., 1997; Y. Liu and J.-H. Tay, 2004, Adav et al., 2008b). Some studies of aerobic granular sludge had been operated on high temperature, e.g., 27-35°C (Liu et al., 2007; Song et al., 2009; Ebrahimi et al., 2010; Muda et al, 2010; Abdullah et al., 2011; Nor-Anuar, 2012; Bassin et al., 2012; Rosman et al., 2013; Othman et al., 2013, Cui F. et al., 2014). A stable and compact AGS structure with good settling ability is reported to be obtained at temperature 30-35°C both by using synthetic (Song et al., 2009; Muda et al., 2010; Nor-Anuar et al. 2012, Bassin et. al, 2012; Cui et al., 2014) and real wastewater (Liu et al., 2007, Nor-Anuar et al., 2012; Othman et al., 2013; Rosman et al., 2013). Besides that, excellent removal performance of COD, Nitrogen and Phosphorus also reported by most researchers with removal efficiency more than 80%.

In the hot climate countries such as in Asia or Arab countries, the temperature of sewage usually varies between 30 to 35°C. Thus, it is necessary for investigation of high temperature effects on aerobic granular sludge be done before the technology can be efficiently scaled-up and put into practice in the countries with high climate. Therefore, the aim of this study was to develop an AGS system for domestic wastewater treatment applications in hot climate and low humidity conditions (e.g. Arab Saudi). In this study, a 4-liter laboratory-scale SBR was designed and used to study the characterization of AGS seeded with domestic sludge from Al-Madina Wastewater Treatment Plant and fed with synthetic wastewater at temperature 30°C. Besides that, the study also was aim to investigate the performance of AGS to remove organic matter (COD) and nutrients (Nitrogen and Phosphorus) simultaneously at 30°C in the AgSBio system.

2. Materials and Methods

2.1. Experimental Procedure and Reactor Operation

Experiments were carried out in a cylindrical column bioreactor (internal diameter of 10 cm and total height of 68.5 cm) with a working volume of 4 L. During the start-up period, 2000 mL of sludge from a municipal sewage treatment plant will be added as the inoculums in bioreactor. The bioreactor will be operated in SBR mode with a cycle of 3 h (180 min and 3 cycles a day) at temperature of 30 ± 1 °C, and DO values be kept below 2 mgL^{-1} without control of pH value. The 3 h cycle of bioreactor operation consists of: 5 min of feeding, 140 min of aerobic reaction, 15-30 min of settling, and 5 min of effluent discharge. A set of two peristaltic pumps were to be used to feed and discharge the wastewater in the bioreactor system. During the filling phase, the influent will be introduced in the reactor through a port located at the bottom of the column. Air will be introduced via a fine bubble aerator at the bottom of the reactor during reaction phase at a flow rate of 2 $Lmin^{-1}$. The wastewater effluent will be withdrawn through an outlet port located at medium height of the bioreactor column, which results in a volumetric exchange ratio (VER) of 50%. The sludge retention time will be set by the discharge of suspended solids with the effluent.

2.2. Synthetic Wastewater Characteristics and Seed Sludge

The bioreactor was fed with synthetic wastewater with composition of the influent media (A) NaAc 65.1 mM, $MgSO_4.7H_2O$ 3.7 mM, KCl 4.8 mM and (B) NH_4Cl 35.2 mM, K_2HPO_4 2.2 mM, KH_2PO_4 4.4 mM (Nor Anuar et. Al., 2007) and 10 mlL^{-1} trace element solution (Vishniac and Santer, 1957). 150 mL of medium A and B would be dosed together with 1500 mL distilled water per cycle. Sodium acetate will be used as the only organic substrate for its biodegradability. The seed sludge would be obtained from Al-Madina Wastewater Treatment Plant, Arab Saudi in order to provide ideal inoculums with ability to acclimatize with low and high temperature conditions. The accepted activated sludge sample will be stored in a cooling room until needed (10 °C). One and half liter of this sample will be seeded in the reactor for the startup stage. It will be aerated for 24 hours and then it will be fed continuously with synthetic wastewater.

2.3. Analytical Methods

The pH and DO were continuously monitored throughout the experiment using an Orion 4-Star Benchtop pH/DO Meter. Parameters such as chemical oxygen demand (COD), BOD_5 ,total nitrogen (TN), total phosphorus (TP), mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS) were carried out according to Standard Methods for the Examination of Water and Wastewater (APHA, 2005). The aerobic granules developed in the SBR were analyzed for their physical characteristics such as size, settling velocity and sludge volume index (SVI). The morphological and structural observations of the granules were conducted periodically by using a stereo microscope equipped with digital image processing and analyzer (PAX-ITv6, ARC PAX-CAM). The microstructure compositions within the granule were observed with a scanning electron microscope (FESEM-Zeiss Supra 35 VPFE-SEM). For the pre-treatment procedure for SEM image, the granules were left dried at room temperature prior to gold sputter coating (Biorad Polaron Division SEM Coating System).

3. Results and Discussion

3.1. Morphology of Aerobic Granular Sludge

Observations of aerobic granules were done periodically under stereomicroscope as shown in Figure 1. At beginning, flocculent sludge with fluffy, loose and irregular shape is predominant in the reactor. Some tiny granules start to appear in the reactor after 7 days of operation. After 2 weeks, dark brown granules which were small in size (average diameter = 1.0–1.5 mm) were observed in the reactor while the sludge flocks gradually disappeared. The granules at this stage were unstable and easily broken up. After 30 days cultivation, large amounts of granules showed near-round shape structure and presented predominantly in the reactor. Cui et al. (2014) reported the shape of the mature granule was close to spherical, which was evidently different from the activated sludge flocs. Attachment of microbes to each other would form a smooth spherical shape of aerobic granules with the EPS distributed through the granules (Zhu et al., 2012). The mature granular structure had a more compact and dense structure and excellent settling ability with maximum diameter 2.87 mm and settling velocity of 38.98 mh^{-1}.

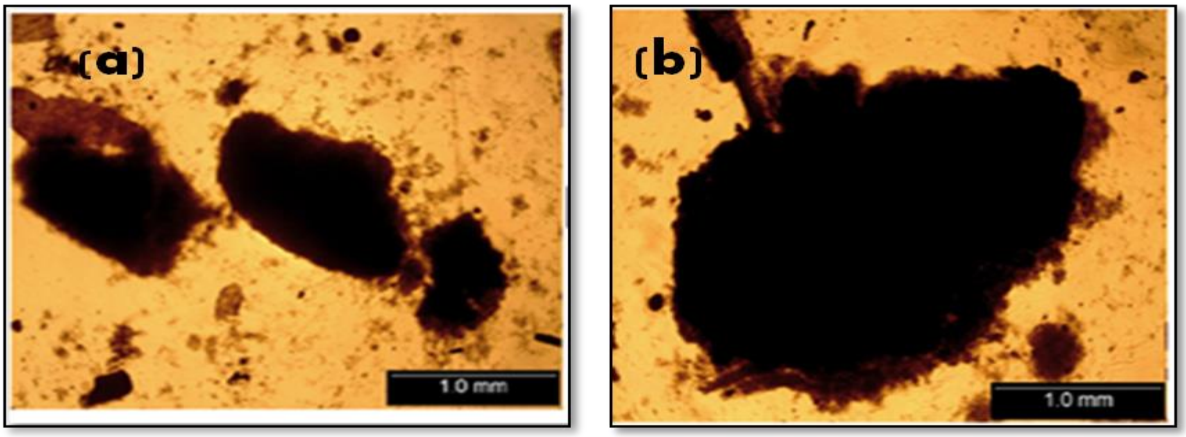

Figure 1. Microscopic observation of granular sludge a) Day 15 (Average ϕ = 1.41 mm, $\upsilon AGS15$ = 21.63 mh^{-1}); b) Day 30 (Average ϕ = 2.87 mm, $\upsilon AGS15$ = 38.98 mh^{-1}).

3.2. Biomass Profile and Settling Characteristics

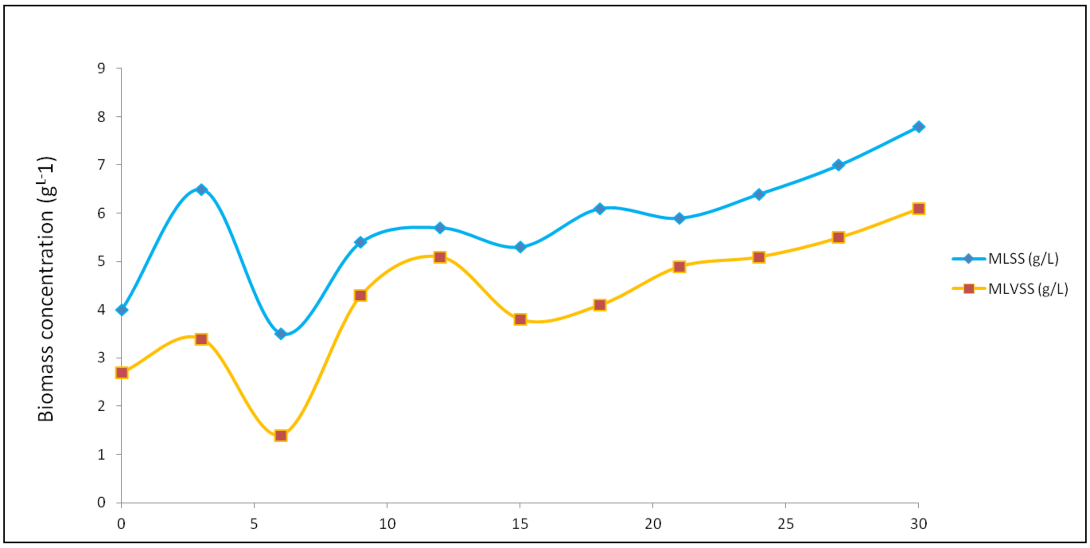

Figure 2. Profiles of biomass concentration for 30 days experiment (◆) MLSS; (■) MLVSS.

Figure 2 illustrates the profile of biomass concentration throughout 30 days of the experimental period. The initial values of MLSS and MLVSS concentration of seed sludge were 4.0 gL^{-1} and 2.7 gL^{-1} respectively. In the first few days, most of the sludge was washed-out from the reactor causing a rapid decrease in the biomass concentration and increased the effluent solids concentration. From day 3 to 9, value of MLSS reduced drastically from 6.5 gL^{-1} to 3.5 gL^{-1} presumably because of the sludge washout and its poor settling properties. The MLSS then increased to 5.7 gL^{-1} on day 12 indicating the high growth of biomass in the reactor. On day 15, value of MLSS reduced again due to washout of the sludge presumably due to formation of granular sludge where small granules (1.0-1.5 mm) were observed in the reactor. In this study, the MLVSS profile showed a similar trend to MLSS. The value of MLSS and MLVSS increased steadily after 15 days of operation and achieved steady state at about 7.8 gL^{-1} and 6.1 gL^{-1}, respectively during days 30, where mature granules with maximum diameter 2.87 mm were observed in the bioreactor. Abdullah et al. (2011) reported that the formation of stable biomass concentration indicates good accumulation of biomass in the reactor. The settling velocity of granules formed increased from 21.63 mh^{-1} to 38.98 mh^{-1}, confirming the fast settling ability of granular sludge compared to conventional bioflocs.

3.3. Removal Efficiencies

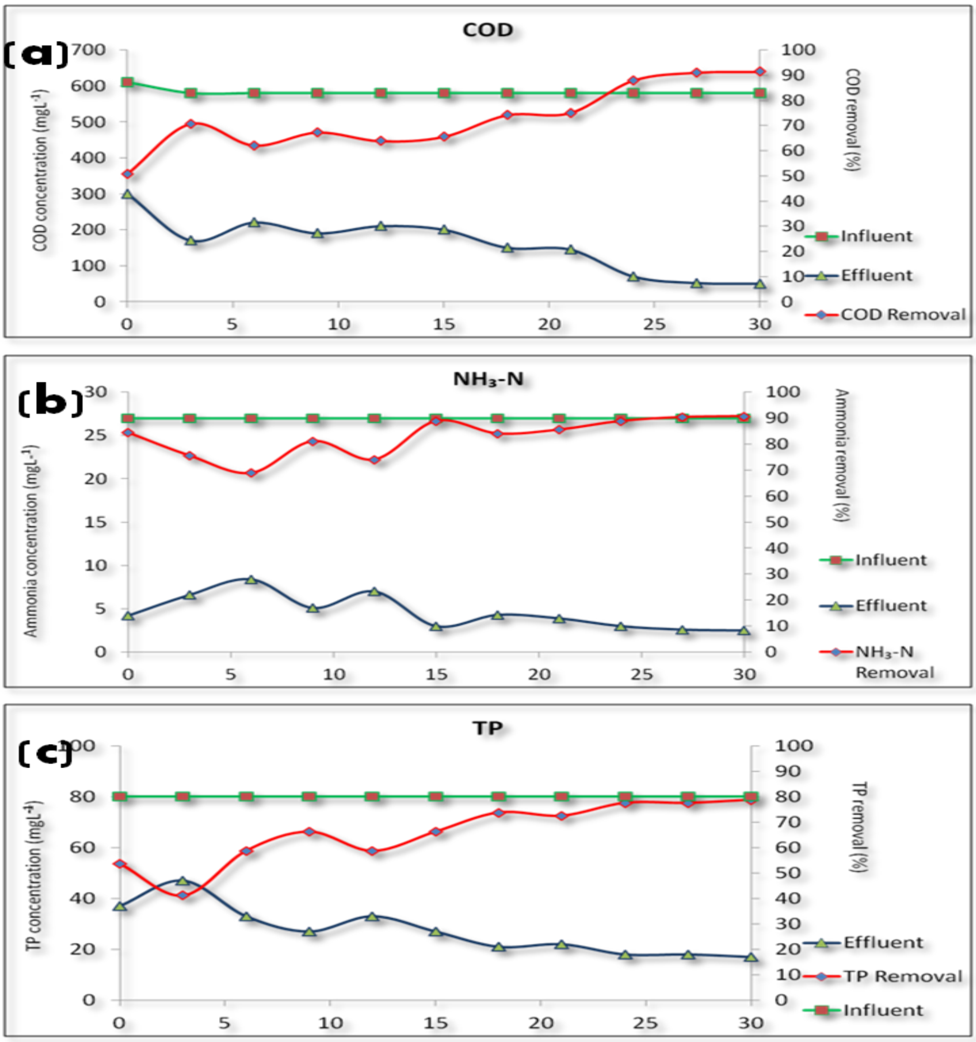

Figure 3. Profile of removal performances in the SBR system within 30 days for (a) COD, (b) Ammonia and (c) TP. (■) Influent Concentration; (▲) Effluent Concentration; (◆) Percentage Removal.

The performance of the reactor with respect to removal efficiencies of COD, NH_3-N, and TP were illustrated in Figure 3. At the beginning, the COD, NH_3-N and TP removal efficiencies fluctuated but became stable after formation of aerobic granules in the second week of the experiment. The COD concentration in the effluent was reduced from 300 mgL^{-1} to 50 mgL^{-1} at the end of experiment, indicating high efficiency of COD removal with percentage up to 91% which is comparable to previous result obtained by Song et al. (2005) in treating domestic wastewater. Rosman et al. (2013) reported that high percentage of COD removal indicates the high biological activity occurred during microbial aerobic degradation process in the bioreactor. The percentage removal of TP was low and fluctuated at the beginning of experiment (53.8% - 66.3%) and then increased as granules were formed and reached removal efficiency up to 78%. The effluent concentration of ammonia was lower than 10 mgL^{-1} and reduced to 2.5 mgL^{-1} with removal efficiency reaching 90%. In most cases, low effluent concentration of COD, Ammonia and TP in wastewater indicates high quality of effluent.

4. Conclusions

The stable aerobic granular sludge fed with synthetic wastewater at 30°C was successfully developed in the SBR system with domestic sludge after 30 days of operation. Mature granules with size ranging from 2.30 to 2.87 mm were observed appearing in the reactor at the end of experiment. Following granulation, the aerobic granules formed a good accumulation of biomass in the reactor with MLSS of 7.8 gL^{-1} and settling velocity of 38.98 mh^{-1}. When tested for COD, ammonia and TP removal, the granules showed 91.38%, 90.74%, 78.75% maximum removal at an OLR of 1.6 kg COD $m^{-3}d^{-1}$ and cycle time of 3 hour operation. The results indicate the feasibility of one single SBR system for the treatment of domestic wastewater.

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