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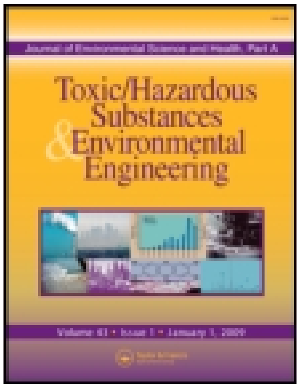

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Wastewater treatment using a modified A2O process based on fiber polypropylene media

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The removal rates of organics and nutrients in municipal wastewater were examined using a laboratory-scale Anaerobic/Anoxic/Oxic (A2O) process modified with fiber polypropylene media at different operational conditions. The system demonstrated excellent performance with the removal rates of chemical oxygen demand (COD), total nitrogen (TN) and total phosphorous (TP) ranging from 91% to 98%, from 48% to 63%, and from 56% to 71%, respectively. Our system was superior to those previously reported based on more complex biofilm reactors, particularly from an economic point of view. For our system, a considerable reduction of COD (55%–68%) occurred even in the anaerobic reactor. The removal rates of COD and nutrients exhibited a slight decreasing trend with a higher organic loading rate (OLR) (0.5 to 2.2 kg COD $m^{-3}day^{-1}$) or with a shorter hydraulic retention time (HRT). The results may be attributed to the competition between nitrifying and heterotrophic bacteria and/or the insufficient time for biological uptake. It is expected that applying fiber polypropylene media to a conventional A2O process may significantly enhance the treatment efficacy of organics and nutrients as a cost-effective strategy.

Keywords: A2O process, fiber polypropylene media, nutrient removal, organic loading rate (OLR), biofilm, municipal wastewater.

Introduction

The accumulation of nutrients in surface waters, especially for nitrogen and phosphorus, can lead to the deterioration of water quality such as algal bloom resulting from eutrophication.[1] In efforts to control the nutrient enrichment in watersheds, various types of operational systems have been tested by wastewater treatment plants (WWTP) with a focus on the simultaneous removal of nitrogen and phosphorus from municipal wastewater. Of those, biological nutrient removal (BNR) processes have been widely employed due to their economic advantages over other physical and chemical treatment methods.[2,3]

BNR processes are generally divided in the two categories of suspended growth and attached growth biofilm processes.[4] The main benefits of the attached growth biofilm type are a relatively short HRT, a long sludge retention time (SRT), a low sludge production, and a high biomass concentration.[4–6] The conventional types of the biofilm systems include trickling filters, biological aerated filters (BAFs), rotating biological contactors (RBCs), fluidized bed reactors (FBRs) and moving bed reactors (MBRs).[7,8] In recent years, however, several technologies based on the modification of the existing BNR processes have been highlighted.

For example, Rodgers et al.[7] proposed a new vertically moving biofilm system for treating municipal wastewater, which has the capability of increasing the removal rates up to 35 g $m^{-2}day^{-1}$ and 25 g $m^{-2}day^{-1}$ for filtered COD and biochemical oxygen demand (BOD), respectively. Patel et al.[9] evaluated the simultaneous removal of carbon (C), nitrogen (N) and phosphorus (P) from municipal wastewater for a circulating fluidized bed bioreactor employing lava rock as the carrier media. They reported the removal rates of 91%, 78% and 85% for C, N and P, respectively, at an empty bed contact time (EBCT) of 0.82 h. More recently, Liu et al.[10] investigated the performance of the BAF employing an oyster shell and a plastic ball as a carrier media. They reported that the average removal rates of COD and ammonia were increased up to over 80% and 94%, respectively, when HRT exceeded 4 h.

Plastic-based biofilm support media have been frequently studied as a supplemental tool for enhancing the performance of the BNR processes.[11] The media are known to be both resistant to attrition and chemically stable, and it also has a high specific surface area and a low apparent specific weight.[12] Many prior studies

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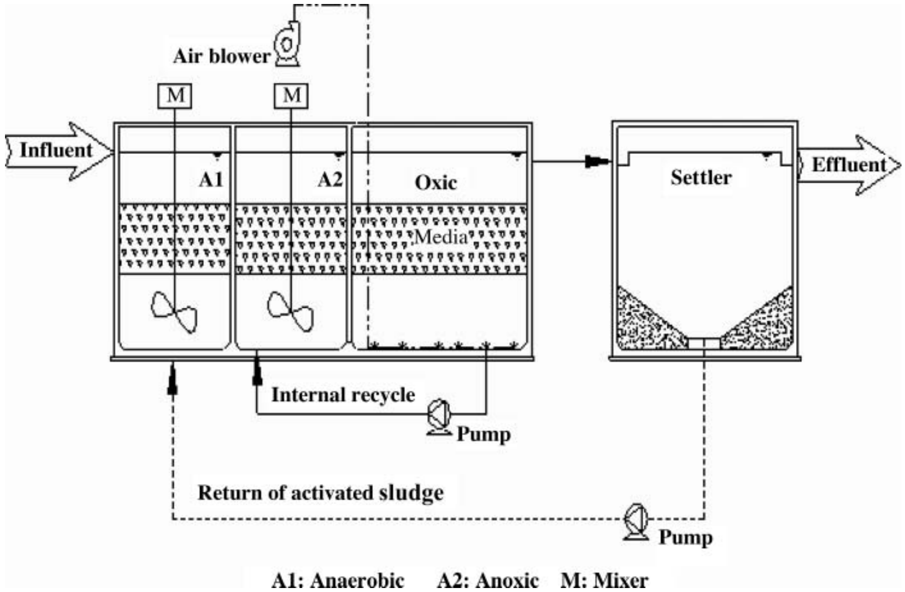

Fig. 1. Schematic diagram of an A2O process modified with fiber polypropylen media for this study.

using plastic media have presented the effective removal of nitrogen and phosphorus from wastewater.[13,14]

The A2O process is the most common and is a well-established BNR process, having gained popularity in many developing countries such as Vietnam and China.[15,16] In this respect, the addition of biofilm media to A2O systems may provide a number of benefits to wastewater treatment in terms of the stability and cost-effectiveness.[6,17] A wide range of different pollutants are likely to be removed due to the existence of more various species of microorganisms living in the media. Moreover, the A2O processes with a packing media may be very attractive for the countries and local governments requiring the construction of economical environmental infrastructures.

For this study, fiber polypropylene media were used to provide extra attachment surfaces for microorganisms in the A2O process. The fiber polypropylene media are known to have several advantages over other biofilm materials including a relatively higher specific surface area and chemical and biological stability.[17] The objectives of this study are (1) to investigate the performance of a A2O process with fiber polypropylene media for the removal of organics, nitrogen and phosphorus at varying OLR, and (2) to evaluate the effects of OLR on the removal performance.

Materials and methods

Experimental setup

Figure 1 shows a schematic diagram of a laboratory-scale A2O system with fiber polypropylene media for this study. The system consists of one anaerobic reactor followed sequentially by an anoxic reactor and an oxic reactor. The treated sample from the oxic reactor is allowed to enter a settler. The net volumes of the anaerobic and the anoxic reactors are equally 4.5 L, and the oxic reactor is 9.0 L. The reactors were filled with fiber polypropylene media, and the packing ratio was 30% based on the volume of each reactor. The picture of fiber polypropylene media is presented in Figure 2.

A bundle of the fiber polypropylene media consisting of thousands of fibres was attached at the center of the reactor (Fig. 1). The fiber polypropylene media has a specific surface area of 300 m^2/m^3, and a specific weight of 0.9 kg/m^3. The average melting point of the raw media is

Fig. 2. Picture of fiber polypropylene media used for this study (color figure available online).

Table 1. Range of concentrations of organics and nutrients for the influent wastewater.

Parameter	*Values (mg L^{-1})*
BOD_5	105–180
COD	200–274
Ammonia	18–26
$NO_2^- + NO_3^-$	0.4–0.9
Suspended solid	100–300
Total Nitrogen	21–30
Total Phosphorus	2.3–3.6

approximately 80°C, and the pH-resistance covers from 2 to 13. Similarly for the typical A2O process, the laboratory system has two recycled flows: one is an internal recycle flow from the oxic reactor to the anoxic reactor for denitrification, and the other is an external recycle flow from the settler to the anaerobic reactor for phosphorus release. The internal and the external recycle ratios remained at 1.0 and 0.5, respectively, based on the influent flow rate. Air was continuously supplied to the oxic reactor by a blower passing through a long stone diffuser at the bottom of the reactor to maintain a dissolved oxygen (DO) level of 2 mg L^{-1} and above.

Wastewater, sludge and sample collection

The wastewater used for this study was collected from the grit sedimentation effluent of a municipal wastewater treatment plant located in Ho Chi Minh City, Vietnam with a treatment capacity of 30,000 m^3 day^{-1}. The influent wastewater was supplied into the laboratory system every two days. The major characteristics are summarized in Table 1. Activated sludge was obtained from a full-scale livestock wastewater treatment plant located in the same city, and it was acclimated to the municipal wastewater of this study at 0.1 kg COD $m^{-3}day^{-1}$ for about 25 days. The operation of the system continued for 112 days, and the effluent samples were regularly collected from the individual reactors at the same interval as the influent supply. During the operation, HRT was changed five times in the order of 2.7, 3.4, 4.8, 8.0 and 12.0 hours to evaluate the effects on the system's performance. The adjustment of the HRT resulted in different OLR values.

Analytical methods

The collected samples were kept in a refrigerator prior to analyses. The concentrations of COD, NH_4^+-N, NO_2^--N, NO_3^--N, TN, and TP were measured according to the standard method for water and wastewater examination.[18] DO concentration and pH were determined on-line using an Oximeter 330 (WTW, Germany) and a pH meter 211 (Hanna, USA), respectively.

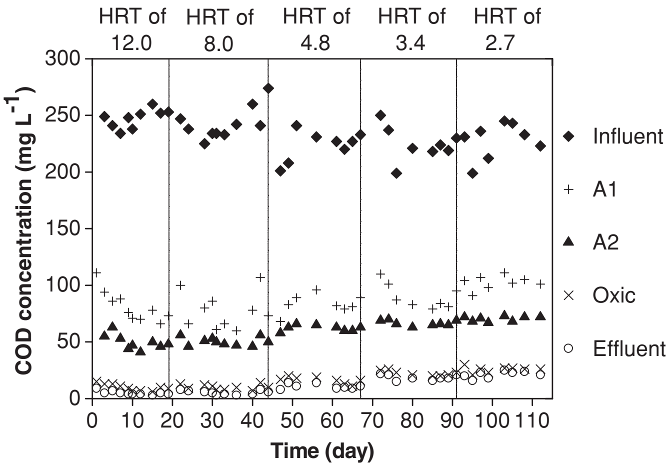

Fig. 3. Variations of COD concentrations for the modified A2O system at different hydraulic retention times.

Results and discussion

COD removal

Changes in COD concentrations for the modified A2O system are shown in Figure 3. The influent concentrations ranged from 200 to 274 mg L^{-1}. A substantial reduction of the COD concentrations was observed after the anaerobic reactor with the removal efficiencies ranging from 55% to 68% at different HRT conditions. Subsequent treatment of the anoxic and the oxic reactors resulted in additional removal of COD from 9.4% to 14.0% and from 16.6% to 20.6%, respectively. Our results indicate that the anaerobic reactor likely play a major role in the COD removal in the system.

Additional removal of COD in the oxic reactor was much less compared to the anaerobic reactor in this system. Similar results were also reported in other studies using an anaerobic-aerobic moving-bed biofilm reactor (MBBR) system.[19] The large removal of COD in the anaerobic reactor may be attributed to the dilution of the external recycle, hydrolysis and fermentation of organic compounds by anaerobic bacteria into end-products such as methane, carbon dioxide, nitrogen or hydrogen sulfide.[20,21] It is reported that the reduction of COD likely occur under anoxic conditions when organics in wastewater is used as an electron donor for denitrification and biological phosphorus release.[20,22] In the oxic reactor, COD is typically decreased via the consumption of heterotrophic bacteria for their growth.[23]

Ammonia and inorganic nitrogen removal

Nitrogen removal in wastewater is typically described as a two-step process. In the first step, called nitrification, ammonia is converted into nitrite by *Nitrosomonas*

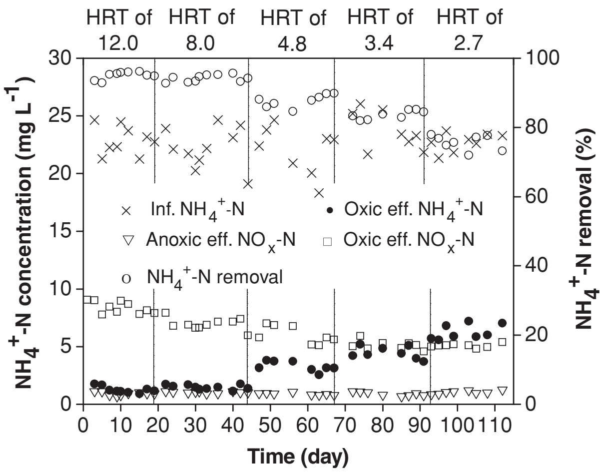

Fig. 4. Variations of inorganic nitrogen concentrations for the modified A2O system at different hydraulic retention times.

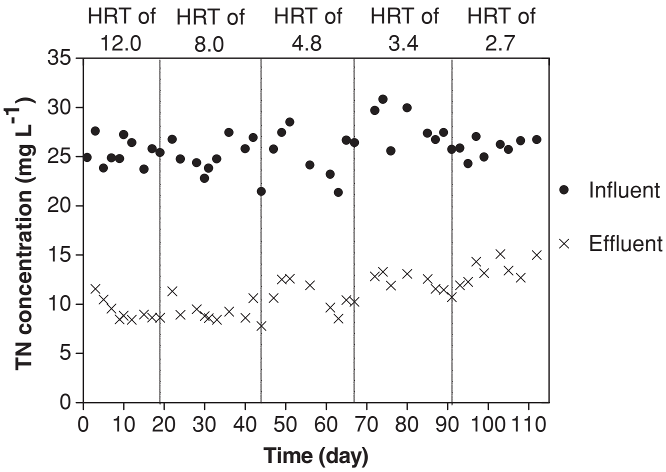

Fig. 5. Variations of the influent and the effluent TN concentrations at different hydraulic retention times.

bacteria and the nitrite is subsequently transformed to nitrate by *Nitrobacter* bacteria under aerobic conditions. In the next step, denitrification occurs under anoxic conditions such that heterotrophic bacteria convert nitrate into gaseous end-products of N_2, NO, or N_2O.[24] Changes in the concentrations of ammonia and inorganic nitrogen in this study are shown in Figure 4. Influent NH_4^+-N concentrations remained in the range of 22.18 ± 3.87 mg L^{-1}.

For relatively long HRTs of 8.0 and 12.0 hours, the average removal efficiencies of NH_4^+-N reached 90% and the effluent concentrations were only 1.2 to 1.3 mg L^{-1}. The low effluent concentrations appear to be associated with the high removal of COD in the anaerobic reactor because a low level of COD would help autotrophic bacteria to grow easily in the subsequent oxic reactor, enhancing the nitrification.[25] For shorter HRTs (i.e., 2.7, 3.4, and 4.8 hours); however, the removal efficiencies fell below 90% and the decrease of the removal became more pronounced for a shorter HRT. This result may be explained by the inhibitory effects of high organic loading on the nitrification process. In general, heterotrophic bacteria tend to exhibit a higher growth rate than nitrifiers (autotrophic bacteria). For wastewater containing a high concentration of organic substances, the growth rate of nitrifiers may be overwhelmed by the rapid growth of heterotrophic bacteria as well as their extensive occupation on biofilm surfaces.[26]

In this study, the effluent NO_x^--N concentration tends to decline with decreasing HRT. Because most effluent NO_x^--N is present as nitrate, this observation may be explained by insufficient contact time between wastewater and biofilm for nitrobacteria to nitrify NH_4^+-N into NO_3^--N.[10]

Variations in the TN concentrations of the influent and the effluent are presented at different HRTs in Figure 5. The concentrations ranged from 21.3 to 30.8 mg L^{-1} for the influent and from 7.8 to 15.1 mg L^{-1} for the effluent. It is interesting that the effluent TN slightly increased with the decrease of HRT from 12.0 to 2.7 h ($r = 0.7$, $p < 0.001$) despite no increasing or decreasing trend observed for the influent TN with HRT. It is reported that the excessive decrease of HRT may induce a decrease of the population of nitrifying bacteria and incomplete nitrification, resulting in the reduction of the nitrogen removal efficiency.[27] This explanation is supported by our observation of the relatively high ratio of NH_4^+-N to TN at the low HRTs (Figs. 4 and 5).

Phosphorus removal

For A2O processes, phosphorous release under anaerobic condition plays an important role in the uptake of phosphorus in the subsequent anoxic and oxic reactors.[28] The results from this study generally follow the typical trends (Fig. 6). Despite considerable variation in the influent, TP concentrations in the anaerobic reactor were consistently higher than the corresponding influent concentrations. In contrast, the anoxic and the oxic reactors exhibited much lower levels of TP.

The exceptions were the cases for the operations under relatively short HRTs of 2.7 and 3.4 hours, in which TP concentrations in the anaerobic reactor were lower than those of the influent. This suggests that biological phosphorous release in the anaerobic reactor is limited by HRT of the system. The relatively lower TP concentration may be attributed to insufficient time for *Acinetobactor ssp*. to selectively uptake substrates into the cells, whereby storing poly-phosphates as the energy source and releasing phosphorus may be limited.[29] It is generally accepted that phosphorus uptake is much lower under anoxic conditions than under aerobic conditions because all phosphorus-accumulating bacteria take up the nutrients under aerobic conditions, whereas only a small proportion of them are involved under anoxic conditions.[30]

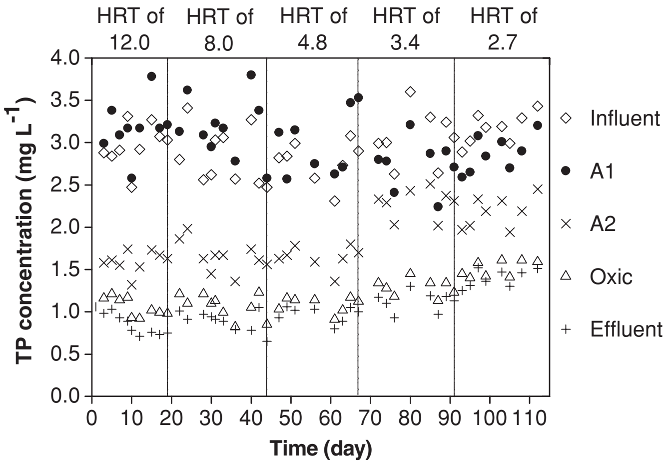

Fig. 6. Variations of TP concentrations for the modified A2O system at different hydraulic retention times.

In this study, however, the amount of phosphorus uptake in the anoxic reactor was not much different from that of the oxic reactor. The difference appears to be affected by HRT. This indicates that an insufficient amount of substrates may be present for cell growth in the oxic reactor. For example, Lee et al.[31] demonstrated in an A2O system packed with granular synthetic activated ceramic that the TP removal rate was much more enhanced by the addition of methanol as the exogenous carbon source compared to those without any additional carbon sources.

Influence of OLR on the removal of organics and nutrients

The removal efficiencies of COD, TN, and TP are illustrated as a function of OLR in Figure 7, which are based on the reconstruction of the data previously presented.

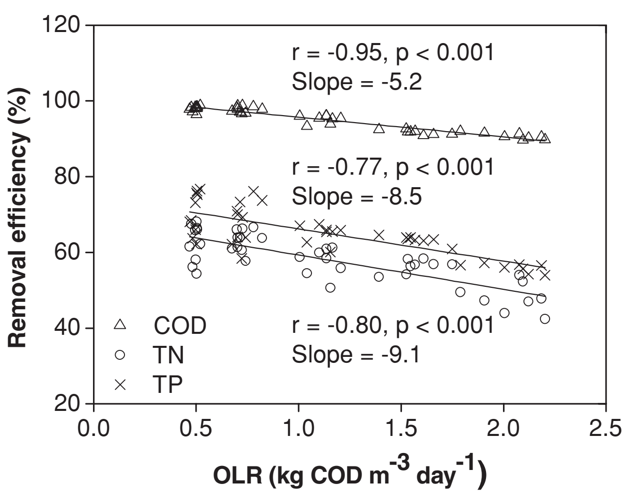

Fig. 7. Correlations between COD, TN and TP removal efficiencies and OLR values.

Irrespective of the types of pollutants, negative correlations were obtained between OLR and the removal efficiencies. This result agrees well with other studies of the modified activated sludge process. For example, Nam et al.[32] observed the enhancement of the removal rates for organics and nutrients with OLR decreasing from 1.2 to 0.5 kg COD $m^{-3}day^{-1}$ under an A2O system filled with synthetic activated ceramic media. More recently, Tizghadam et al.[33] reported using a novel hybrid activated sludge baffled reactor with both suspended and attached-growth biomass in series in which the COD removal rate was decreased from 98% to 90% with OLR varying from 1.4 to 5.6 kg COD $m^{-3}day^{-1}$.

It is notable that the COD removal efficiencies exhibited a steady decreasing trend with a higher OLR while they remained relatively high levels of >90%. This demonstrates that our modified A2O process has a high COD removal capability even under a high level of organic loading (up to 2.25 kg COD $m^{-3}day^{-1}$). The steadily good COD removal performance may be attributed to synergistic effects from different species of microorganisms grown in the polypropylene biofilm. Similar trends are also found in other prior studies using biofilm media. For example, the COD removal efficiency of a biological synthetic activated ceramic nutrient removal process exhibited a range between 90.5% and 97.5%, with OLR varying from 0.48 to 1.2 kg COD $m^{-3}day^{-1}$.[29] Nam et al.[23] reported COD removal efficiency of 87.2% to 89.6% at an OLR of 1.15 kg COD $m^{-3}day^{-1}$ in an A2O system packed with net-type SARAN media. More recently, Peng et al.[2], using a complex A2O system consisting of eight reactors, demonstrated a high COD removal efficiency of 92.3% at an average influent COD concentration of 343 mg L^{-1}. It is noteworthy that our system requires much less energy and construction cost compared to other systems previously mentioned even though it has comparable performance for COD removal.

Likewise the COD removal, the removal efficiencies of TN and TP decreased with a higher OLR, varying from 62.6% to 48.0%, and from 70.5% to 55.9%, respectively. The negative relationship between the TN removal rate and OLR may be related to the low nitrification efficiency as previously discussed. In the oxic reactor, nitrification takes place at biofilm interfaces present in oxic layers, whereas denitrification may occur in deeper layers of the biofilm where the anoxic condition is predominant.[34]

Our modified A2O process demonstrated the superiority of TN removal over other similar systems. For example, a recent study of an anoxic-oxic biofilm process with submerged iron media had shown a maximum TN removal efficiency of only 53.9% but the influent concentration was similar to that of this study.[35] Fan et al.[3] used a full scale modified A2O system consisting of pre-anoxic/anaerobic/anoxic/3-stage oxic reactors, and they showed an average TN removal efficiency of 25% at an internal recycle flow ratio of 0.5. The excellence in the TN removal of our system may be explained by a high concentration of nitrifying bacteria in the polypropylene media and relatively a high internal recycle ratio (i.e., 1.0). Baeza et al.[36] have demonstrated that an increase in the internal recycle flow ratio may be beneficial for nitrogen removal efficiency in a pilot-scale A2O wastewater treatment plant.

The TP removal efficiency also showed a decreasing trend with increasing OLR (Fig. 7). Again, the increased OLR (i.e., shorter HRT) appears to cause insufficient time for PAOs (phosphorous accumulating organisms) to uptake phosphorous in the oxic reactor.[37] The deficient retention time in a system may also affect the activity of PAOs in the anaerobic reactor, limiting its assimilation of readily available organic matter to poly-hydroxyalkanoates (PHAs) by utilizing poly-phosphates stored in the cell as energy sources.[38]

TN removal efficiency showed the steepest slope among the regression equations we investigated, implying its highest dependency on ORL (Fig. 7). This result may be attributed to the combined effects of nitrifier and heterotrophic bacteria in the oxic reactor as well as the insufficient contact time in the system for bacterial uptake.

Conclusion

A laboratory-scale A2O process using fiber polypropylene media demonstrated excellent performance for the removal of COD, TN and TP, ranging from 91% to 98%, from 48% to 63%, and from 56% to 71%, respectively. The high removal efficiencies were comparable to those reported in other studies using more complex reactors and/or more expensive biofilm media, suggesting that our system is very cost-effective. A considerable reduction of COD (55% 68%) occurred even in the anaerobic reactor of our system. The removal rates of TN and TP showed a decreasing trend with a higher OLR or a shorter HRT. The effects of changing operational conditions are possibly explained by the competition between nitrifying and heterotrophic bacteria and the insufficient time for biological uptake. The highest dependency of the removal efficiencies on ORL was exhibited for TN, in which bacterial competition and the insufficient contact time both play roles in the removal process.

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