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Grey water reuse of a multi-functional super-high building: evaluation of model treatment processes

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ABSTRACT

Grey water is an important alternative water resource which can reduce fresh water consumption, especially in cities. Potential treatment processes for grey water reuse of a multi-functional super-high building (632 m in height) were screened based on evaluation of wastewater quality and pilot studies. The biological activated carbon (BAC) and the membrane bio-reactor (MBR) processes were evaluated as two candidate biological systems; while the coagulation-floatation process was used as pre-treatment for both systems. Although the two systems produced effluent water with similar removing performances in chemical oxygen demand (CODcr), the MBR system was more efficient in removing other pollutants such as ammonia and Linear Alklybezene Sulfonates (LAS). The combination of coagulation-floatation pre-treatment and the MBR system proved to be a suitable treatment/reuse process for the super-high building; while the pre-treatment can be omitted when the influent LAS is less than 10 mg/L, in which case effluent CODcr of the MBR system reached 16–45 mg/L with a total hydraulic retention time as short as 7.6 h. This study provides a valuable reference for grey water reuse in super-high buildings.

Keywords: Super-high building; Grey water; Biological activated carbon (BAC); Membrane bioreactor (MBR); Pre-treatment

1. Introduction

Grey water is generated from activities such as bathing, hand washing, cloth washing, dish washing, but excluding wastewater from toilets [1,2]. Characteristics of grey water vary greatly and are tedious to predict [3]. Phosphorus, heavy metals and synthetic organic pollutants in grey water are about the same concentrations as in municipal wastewater while the content of ammonia (NH_3-N) and total kjeldahl nitrogen (TKN) is lower, and it contains less nitrogen-suspended solids (SS) and pathogens than blackwater [2].

Treated grey water can be used in many aspects including flushing, cleaning and irrigation [4], by which means individual in-house net water demand may be reduced by 40–60 L/d per capita [5,6]. Challenging pollutants in grey water are mainly coming from household chemical products such as detergents, soap, shampoo, toothpaste, and a variety of solvents, where linear alklybezene sulfonates (LAS) are the most employed surfactants in the formulation of laundry and personal cleaning products [7].

The Shanghai Tower is located at Z3-2 block, unit E14 of the Pudong Lujiazui Financial District, close to the Huangpu River Shore. The building is 632 m in total height with a structure height of 565.6 m, which makes it the tallest constructed building in China. Main functions of the building are offices, hotels, and commercial entertainment. The Shanghai tower located in the most prosperous area in shanghai, where the house price is so high that the space used for grey water reuse is limited; at the same time since

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the total height and water consumption would be too large to be centralized in the basement, some of the water reuse facilities should also be settled at middle floors of the building. Considering the structure's load-bearing, the selected process should be compact in area. Furthermore grey water treatment for the super-high buildings should be very effective in removing the organic matter and pathogens and producing safe quality effluent to meet the required reuse standards [8].

Various technologies have been applied to reuse grey water including physical treatment technologies such as soil filtration and direct ultrafiltration [9,10], chemical treatment technologies such as chemical coagulation and electro-coagulation [11,12] and biological treatment technologies such as biological contactor, anaerobic biofilms and membrane bioreactor [13,14]. The selected processes for grey water reuse in super-high buildings should have a good quality of effluent with less secondary pollution and easy to operate. Biological treatment technologies are considered to be a suitable choice for grey water treatment due to the high efficiency, cheap and easy operation requirements [15]. Among various biological wastewater treatment technologies, the membrane bio-reactor (MBR) and biological activated carbon (BAC) processes are of particular interests [16]. MBR is an advanced biological wastewater treatment technology which uses ultra-or micro-filtration membrane modules to achieve solids separation [17], which provides several substantial improvements compared to conventional biological processes. The implementation of membrane lead to steady and good effluent quality, small space need and fewer waste sludge [18]; A submerged MBR was proved to be efficient in removing COD, NH_3-N, turbidity and color of grey water [19]. In general, the MBR technology can reduce the area for grey water treatment significantly and save civil construction investment, which is suitable for super-high buildings; BAC treatment has also been proved to be an efficient and mature technology to treat wastewater [20]. The major advantage for the BAC process is that the refractory organic matters will be absorbed into macrospores where it can be detained for a long time and be biodegraded by microorganisms [21]. Most of these technologies are not very effective when used individually. Biological treatment processes that rely mainly on microorganisms can achieve a high efficiency in removing organic pollutants; however, it also produces a large amount of waste sludge and needs large reactor volume. Thus bio-treatment processes were necessary to be combined with pre-treatment technologies; as an example a study found that combining an electro-coagulation unit with a submerged membrane bioreactor can improve overall performance of the membrane filtration process [22].

Few studies have been conducted to treat grey water in super-high buildings, in which case not only the pollutants including COD, NH_3-N and LAS need to be removed efficiently, but also the odor produced during grey water treatment and water pressure demand are also a challenge. A study conducted in UK showed that operating costs for grey water reuse in high buildings were much higher than in other buildings and it is important to improve the efficiency of the treatment facilities through optimization techniques [23]. This study aims to screen a suitable cost-effective treatment process to reuse grey water inside the Shanghai Tower (a super-high building) based on evaluation of grey water quality and pilot studies for miscellaneous purposes such as toilet flushing, watering and waterscape. Pilot-scale experiments were conducted on two typical grey water treatment processes i.e. the pre-treatment + MBR process and the pre-treatment + BAC process. The pre-treatment coagulation-floatation process was optimized and then the main biochemical processing unit was screened. Two typical processes for grey water treatment were compared.

2. Materials and methods

2.1. Set-up of the pre-treatment unit

The air floating device was built with steel plate. It composed of a mixing/reaction zone and an air floating zone. The capacity of the pre-treatment unit is 2.0 m^3/h with a design-surface load of 1.1 $m^3/m^2/h$. The whole volume of the device is 2.0 m^3, including 0.2 m^3 for the sludge zone and 0.6 m^3 for the coagulation reaction chamber. 25 mg/L $Al_2(SO_4)_3$ was dosed as the coagulant with a hydraulic residence time of 1.42 h. The contact time for coagulants was 6 min.

2.2. Set-up of the MBR process

An immersed ultra-filtration system using a vertical LGJ1E1-1100×6 membrane box was used for the MBR process (Lisheng, China). The membrane is made of flat cassette-type poly-vinylidenefluoride (PVDF) with an average pore size of 0.02 μm and an effective fiber diameter size of 1.8 mm. The designed membrane flux was 12.8 $L/m^2/h$ and area of the effective filtration surface was 78 m^2. The volumes for the anaerobic zone, anoxic zone and aerobic zones are 1.8 m^3, 1.8 m^3 and 5.0 m^3 respectively. The air inflow rate was maintained at 0.4 m^3/h. An automated controlling system was used to control four steps of the process i.e. filtering, backwashing, chemical cleaning and chemical maintenance. The MBR process was operated periodically: for every 8 h, 3 m^3 of grey water was pumped into the MBR reactors within 30 min and catered to the filling-reacting-discharging cycle. Operational conditions of the MBR system involved a 120-min production phase (1 m^3/h), followed by a 20-min backwashing; the inflow and suction time were automatically controlled by the liquid level with a batch influent. Operational trans-membrane pressure of the vacuum module was between 60 KPa minus and 40 KPa minus. The MBR process was continuously aerated.

2.3. Set-up of the BAC process

Total height of the BAC column was 2.5 m with a diameter of 0.3 m and a cross-sectional area of 0.071 m^2. The height of packing layer inside the filter was 1.5 m with an average support layer of 0.2 m. Influent flow rate of the BAC process was set as 1.0 m^3/h. When the pressure of the filter is greater than or equal to 0.05 MPa, the filter would be backwashed. Porous aerator was set up at the bottom of the BAC filter with continuous aeration by an air compressor; maximum air inflow to the BAC was set as 60.0 m^3/h. Every 48 min, 0.3 m^3 of grey water will be pumped within 2 min into the BAC reactors and catered to the filling-reacting-discharging cycle. The BAC process was continuously aerated.

2.4. Start-up of the study processes

The grey water used in the present study was collected from the offices and apartments and stored in the equalization tank located at B$_5$ floor of the super-high building; the experimental setup of this study is shown in Fig. 1. The grey water was continuous loaded to devices for the first 20 d and then followed by the intermittent mode for 15 d. The influent flow rate for both BAC and MBR processes was 1.3 m^3/h with an influent LAS concentration around 10 mg/L during the start-up period. HRT of the MBR process was 8.33 h with an operational membrane flux of 10.3 L/m^2/h. The BAC was using an up-flow mode and then modified to a down-flow mode according to the pilot test results; surface load for the BAC process was 4.2 m^3/m^2/h, with a total HRT of 21.3 min.

2.5. Determination of waste water parameters

Parameters including temperature, pH, dissolved oxygen (DO), NH$_3$-N, nitrite (NO$_2^-$-N), nitrate(NO$_3^-$-N), total nitrogen (TN), total phosphorus (TP), mixed liquid suspended solid (MLSS), volatile suspended solids (VSS), SS, LAS and CODcr were measured as described in standard methods [24]. Total organic carbon (TOC) was analyzed with a multi N/C 3100 analyzer and turbidity with a HACH 2100N turbid meter.

3. Results and discussion

3.1. Characteristics of the wastewater

Quality parameters of the raw grey water are listed in Table 1. The concentration of NH$_3$-N varied from 0.8 to 5.6 mg/L; TN varied from 5.8 to 25.0 mg/L and TP from 0.4 to 2.9 mg/L. The water quality is similar to a low-medium strength municipal wastewater in terms of organic

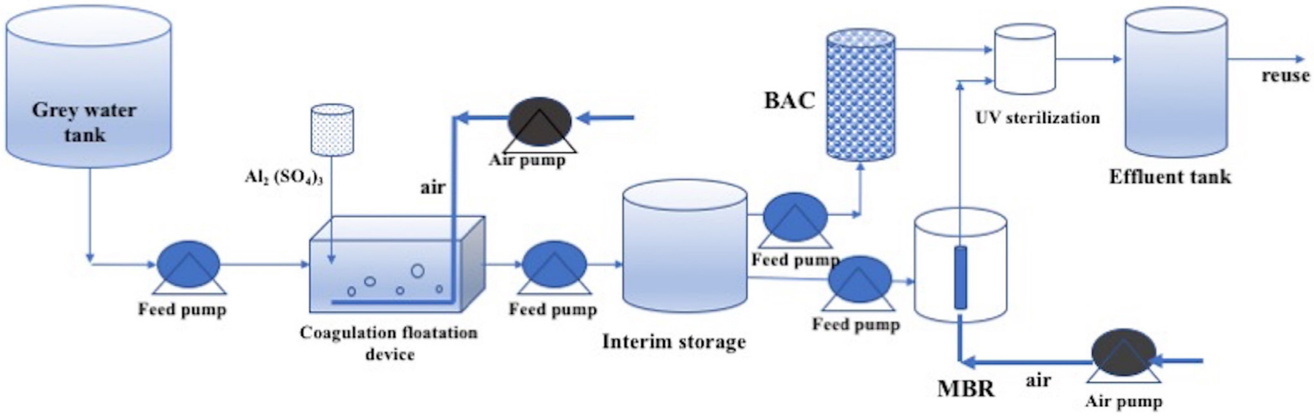

Fig. 1. Diagram of the experimental setup.

Table 1
Monthly variation of selected parameters of the study grey water

Month	COD	TSS	SS	VSS	TOC	TN	TP	NO$_3$-N	NH$_3$-N	PO$_4^-$-P	LAS
Mar	391.6	956.0	201.6	161.3	63.4	5.8	1.0	0.6	2.4	0.1	15.5
Apr	293.7	443.5	144.0	132.5	63.4	6.9	0.4	0.7	2.2	0.1	9.1
May	305.2	414.7	224.6	178.5	11.5	7.4	1.1	0.6	3.4	0.1	5.7
Jun	293.7	374.4	138.2	57.6	149.7	7.7	2.9	0.8	5.6	0.6	1.1
Jul	195.8	437.7	46.1	40.3	120.9	24.9	0.4	0.8	4.7	0.3	1.1
Aug	431.9	362.8	178.5	138.2	23.0	8.5	0.8	0.9	4.2	0.5	8.7
Sep	403.1	334.0	270.7	97.9	23.0	10.1	0.7	0.8	4.0	0.3	3.4
Oct	478.0	789.0	253.4	207.3	17.3	16.0	1.8	0.7	4.9	0.5	2.8
Nov	408.9	679.6	564.4	178.5	144.0	16.1	0.4	1.0	4.1	0.1	5.1
Dec	460.7	685.3	322.5	57.6	69.1	18.4	1.9	2.2	3.0	1.1	4.5
Jan	627.8	956.0	570.2	512.6	132.5	20.1	0.8	0.1	0.8	0.1	5.4
Feb	547.1	944.5	224.6	178.5	46.1	18.2	1.1	0.8	1.5	0.1	4.5
Average	403.1	614.8	261.6	161.7	72.0	13.3	1.1	0.8	3.4	0.3	5.6
Standard deviation	120.6	234.8	168.5	136.1	52.8	5.4	0.8	0.5	1.5	0.3	2.2

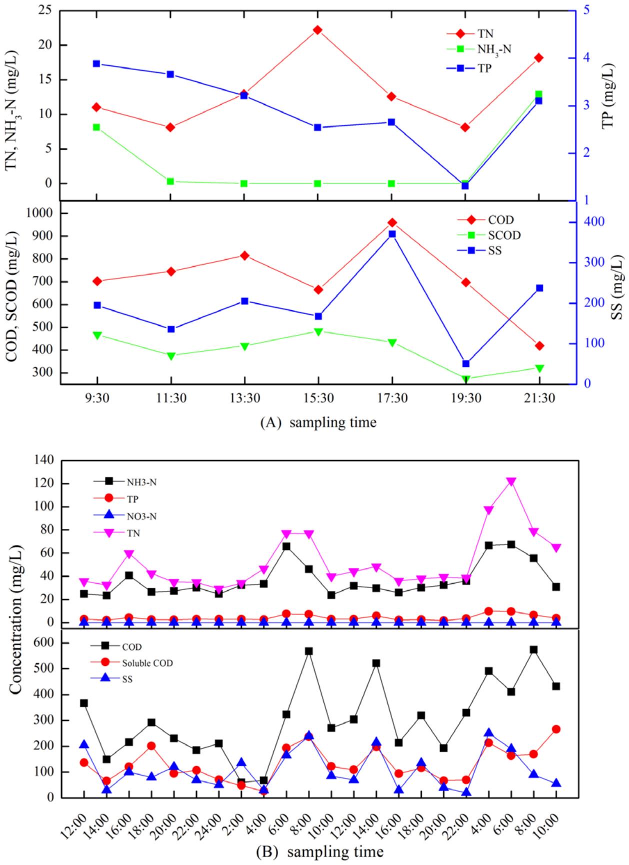

Fig. 2. Variation of grey water quality, where (A) mixed with black water and (B) black water excluded.

strength, but comparable to a tertiary sewage effluent in terms of the biodegradability and the physical pollutants content [24].Concentrations of TN and NH_3-N were much less than domestic wastewater (usually in the range of 30.0–50.0 mg/L), but close to the bathing wastewater. As shown in Table 1, main pollutants of the grey water changed with seasons. The average concentration of COD_{Cr}, VSS and SS in summer were 307.2, 78.7 and 120.9 mg/L respectively, which were only 50%~60% of that in other seasons. LAS concentration of the grey water varied from 1.1 to 15.5 mg/L with an average value of 6.3 mg/L. The highest LAS concentration occurred in summer when the temperature is higher than in other seasons. Comparatively TP, NH_3-N, NO_3-N, PO_4-P and TOC showed smaller variations with seasons.

A typical day was chosen in the summer to show daily change of main parameters of the grey water (Fig. 2). CODcr concentration in Fig. 2A was higher than traditional grey water due to a small amount of blackwater mixed in the wastewater. The concentration of the soluble CODcr (SCOD), however, kept in the same range of 270.0–450.0 mg/L comparing with grey water from other buildings. SS concentration was between 46.0 mg/L and 570.0 mg/L. The discharging volume of grey water varies with the functions of buildings such as single-family houses, housing settlements, hotels and camping sites and shopping malls [25]. The water consumption in different functional buildings has a great influence on water quality of grey water. The greater the water volume consumed, the more likely the concentration of pollutants is lower. Two days' variation of TN, NH_3-N, NO_3-N and TP concentrations were shown in Fig. 2B. There are two daily peaks for the discharging volume of grey water from the building: one is from 6:00 to 8:00 AM, and the other is from 16:00 to 19:00 PM. At the same time the dynamic changes of SCOD, SS and TN are found to be inter-acting with the changing of the discharging volume of grey water.

3.2. Start-up characteristics of the study processes

The change of CODcr and NH_3-N concentration during the start-up period are shown in Fig. 3. Fig. 3A indicated that the influent NH_3-N concentration varied from 21.1 to 66.5 mg/L with an average value of 33.3 mg/L; but it shows little decrease after coagulation-floatation and BAC treatment; while NH_3-N concentration decreases from 33.3 mg/L to 2.3 mg/L with a removal rate of 93.4% after treated by the MBR process. The average influent CODcr concentration was 300 mg/L and decreased to 150 mg/L after coagulation-floatation pre-treatment; the average effluent CODcr concentration of the BAC and MBR processes were 64.2 mg/L and 37.9 mg/L with average removal rates of 74.4% and 85.0% respectively (Fig. 3B). The lower removal efficiency of NH_3-N in the BAC process might be attributed to the in-sufficient contact time within the down-flow activated filter bed that led to poor nitrification. Therefore, a modification could be made to increase HRT and change the BAC process to an up-flow mode.

3.3. Modification of operational modes

Apart from poor nitrification in the down-flow mode, it is also found that the influent SS during the start-up operation could lead to operational difficulties of the BAC process. The MBR process runs more smoothly than the BAC process, but poor TN and TP removal performance is also troublesome for the AO-MBR (anaerobic-oxic) system. The BAC process was then modified to an up-flow mode ; while an extra anoxic zone was divided from the old chamber to improve the removal efficiency of TN and TP for the MBR process. After modification, the MBR process was operated under an A^2O-MBR (anaerobic-anoxic-oxic) mode.

The MLSS concentration in the A^2O-MBR ranged from 4000 to 5000 mg/L with a membrane flux of 12.8 L/h; the total HRT was 11.4 h including 6.7 h of aerobic HRT. Surface load for the modified BAC process was 2.8 $m^3/m^2/$hand the the empty bed residence time was 32 min. Fig. 4 demonstrated CODcr, NH_3-N and TN profiles present for a 45 d operational period. In Fig. 4A, the inflow CODcr concentration ranged from 112 to 208 mg/L with an average of 192.9 mg/L, after treated with the BAC process it decreased to 65.5 mg/L with an average removal rate of 77.8%. While average effluent CODcr concentration of the MBR process was 25.1 mg/L; CODcr removal efficiency of the BAC process was lower due to the limited contact time between wastewater and microorganism in reactor [26]. It can be found from Fig. 4B that the average inflow NH_3-N concentration is 30 mg/L and it changed little after BAC treatment with a removal rate of only 6%. On the contrary MBR process is very efficient in removing NH_3-N; the aver-

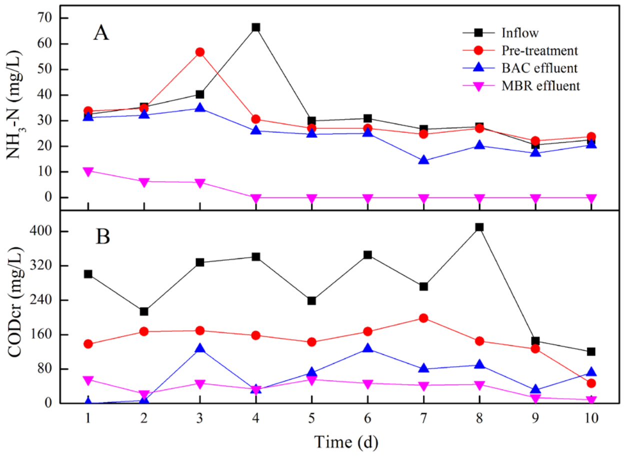

Fig. 3. COD and NH_3-N treatment profiles of both processes; the BAC process is using an up-flow mode.

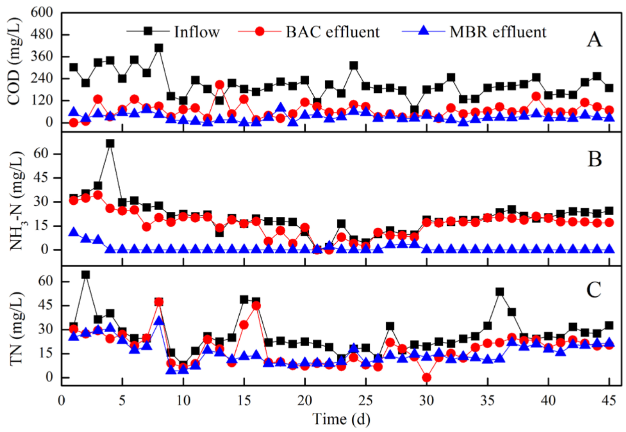

Fig. 4. CODcr, NH_3-N and TN treatment profiles of the modified processes.

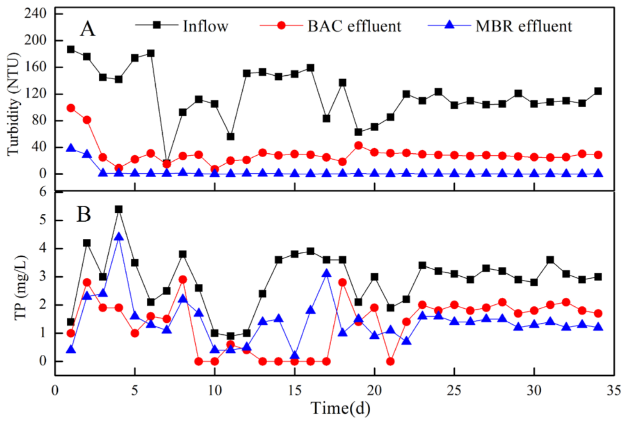

Fig. 5. TP and turbidity treatment profiles of the modified processes.

age effluent NH_3-N concentration is 1 mg/L with a removal rate of 96%. Variation of TN concentration during treatments was shown in Fig. 4C with an influent concentration ranging from 15 to 45 mg/L; TN removal efficiencies for the MBR process and the BAC process were comparable with removal rates of 52% and 50% respectively.

Fig. 5 demonstrated TP and turbidity treatment profiles of the study processes. The influent turbidity fluctuates greatly in the first 20 d with continuous operation and gradually stabilized in the next 15 d using intermittent operation with an average value of 157.3 NTU (Fig. 5A). After treated with the BAC process the turbidity decreased to 30 NTU with a removal rate of 81%; while the turbidity decreased to 0.3–0.9 NTU after MBR treatment with an average removal rate of 99.6%. The effluent turbidity of the BAC process was considerably higher than the MBR process both with continuous operation and intermittent operation due to the existence of ultra-filtration membrane in the MBR process which can obstruct most of the suspended solid. Fig. 5B indicated that during the first 20 days of continuous operation, the BAC process is more efficient in removing TP than the MBR process, with TP removal rates of 44.4% and 33.3% respectively for the two processes. The change of TP concentration turns to be stable during the intermittent operation period with the averaged effluent TP concentrations for the BAC process and the MBR process as 2.0 and 1.2 mg/L respectively. It can be found that the BAC process achieved a better performance under the intermittent mode than the continuous mode due to longer contact time of adsorption, though the reaction time for the bio-degradation is identical for both operational modes. The effluent water quality of the MBR process is about the same level with both intermittent and continuous operational modes since bio-adsorption is less important than bio-degradation in the process.

The surface load of the BAC system is 2.8 $m^3/m^2/h$ with a hydraulic load ranging from 2.0–10.0 $m^3/m^2/h$. A suitable ammonia nitrogen volume load of the BAC system was in the range of 0.10–0.77kg-NH_3-N/m^3/d at 20°C. Increasing hydraulic retention time of the BAC process, or multi-level BAC filters was suggested to improve carbonization and nitration for the BAC process [16]. The MBR system had a better nitrification performance because of its higher aeration rate and lower organic load. Intermittent operation is more efficient in removing pollutants and keeping the system stable.

Performances of LAS removal for both processes are shown in Fig. 6. The influent LAS concentration remained relatively constant in sampling days, and the removal rate of the pre-treatment was around 40%. LAS can be reduced for about 60% after the BAC process; while the MBR process presented higher efficiency in removing LAS with an average effluent concentration of 0.4 mg/L, which is comparable to some studies concluding that LAS will lose tonic activity rapidly and be bio-degraded easily in well designed wastewater treatment plants [27]. The different LAS removal performances of the two study processes may result from two major reasons: (i) the suspended biomass (MLSS) in the MBR process had a larger surface area than biofilms in the BAC process, which enhanced the adsorption of LAS, (ii) the residence time of LAS in the MBR was longer than in the BAC process, which enhanced bio-degradation of LAS in the system.

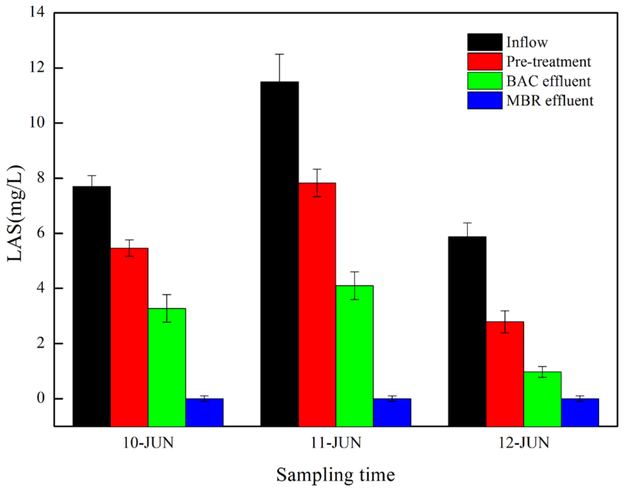

Fig. 6. LAS removal of the modified BAC and MBR processes.

3.4. Implications of grey water treatment in super-high buildings

The BAC process is an optional biological treatment strategy for grey water reuse [28]. However, it presented lower removal efficiencies on CODcr, NH_3-N, TN, TP and LAS than the MBR process in this study. The remaining SS and turbidity after pre-treatment were still quite high, which will cause blockage of the activated carbon layer. The MBR process had a higher removal efficiency with an effluent turbidity lower than 1.0 NTU; however effluent soluble microbial products (SMPs) in MBRs are still high, which could easily lead to membrane fouling [29]. TN and TP removal rates of the MBR process can be further improved if the coagulation-floatation pre-treatment can be omitted, since much of the influent CODcr had been removed during the pre-treatment, which leads to low sludge concentration and poor TN/TP removal capacity.

Due to special features of the Shanghai Tower, the grey water flow last for only 8 h/d and no raw water would input for the other 16 h. Two methods are proposed to solve the problem. One option is to build a large equalization tank and another is to exploit the shock load capacity of the biochemical system to its maximum capacity and reduce volume of the equalization tank. Taken factors such as limited mechanical room capacity in the Shanghai Tower for consideration, and conditions of structure bearing load of the device floor as well, the second method should be the preferential option. The BAC process turned out to be an outstanding method in terms of hydraulic load, but its effluent water quality was unable to meet reuse requirements, especially in terms of ammonium concentration. Besides, the operation and maintenance of the BAC process is more complicated compared to the MBR process [30]. For traditional wastewater treatment processes the energy consumption was reported to be 0.3–0.4 kWh/m^3 [31]. For other grey water treatment technologies such as filtration and absorption, the filters need to be replaced periodically and large numbers of chemical reagents and/or external electricity were needed in many treatment technologies such as chemical coagulation and eletro-coagulation. Based on characteristics of the modified MBR process in the present study, the removal efficiency of grey water treatment under intermittent operation is higher than continuous operation, which can also save a large amount of energy. It had been reported that the energy consumption was only 0.02–0.04 kWh/m^3 in a modified gravity-driven MBR system for grey water treatment [32].

4. Conclusions

More than half of the domestic water consumption is turned into grey water, which represents a substantial resource if it can be reused safely. Take Shanghai Tower for example, the coagulation-floatation + MBR process was confirmed to be a feasible method to treat and reuse grey water in super-high buildings. The effluent CODcr concentration of the process was from 16 to 45 mg/L and there was nearly no ammonia detected in the effluent. The MBR process was proved to be more efficient in eliminating pollutants such as CODcr and LAS that can meet reuse requirements for water quality than the BAC process; the effluent can be used for urban miscellaneous water and landscape water.

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