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A prototype IT/BF–MBR (inclined tube/biofilm-membrane bioreactor) for high-rise building wastewater recycling

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ABSTRACT

A novel inclined-tube biofilm-membrane bioreactor (IT/BF-MBR) has been developed in a prototype system for high-rise building wastewater recycling. The prototype IT/BF-MBR system was designed as a single compact reactor with three compartments, starting from first-stage biofilm compartment, second-stage biofilm compartment and aerobic membrane compartment with submerged MF membrane installation. Here, the inclined tube was installed as a prefilter for sieving and filtering the incoming suspended solid and also served as a media to promote biofilm growth in the biofilm compartments to enhance more biomass activity inside the IT/BF-MBR system. The system received raw wastewater from a 20-floor university building at a design flow rate capacity of 4 m^3/day. The IT/BF-MBR could achieve stable treatment performance as above 90% removal efficiencies for organic Chemical oxygen demand, NH_4^+–N, and total phosphorus. The composition of microbial EPS inside the membrane bioreactor system was found in the following order: lipid > carbohydrate > protein. Furthermore, the quality of treated effluent could comply with the reuse water quality standard for nonpotable uses as toilet flushing and garden watering purposes.

Keywords: Inclined tube/biofilm-membrane bioreactor (IT/BF-MBR); High-rise building; Wastewater recycling; Prototype system; Microbial EPS (extracellular polymeric substances); Nonpotable reuse purposes

1. Introduction

Recently, high-rise buildings have been recognized as one of main sources of water pollution in cities if their wastewaters are not appropriately handled. Environmental impact of nutrients especially nitrogen and phosphorus from high-rise building on deterioration in water quality of water resources is one of the main concerns, since nitrogen and phosphorus are biostimulants for the growth of aquatic plants. Various studies on wastewater treatment and recycling by submerged membrane bioreactor (MBR) have been performed using raw wastewater from domestic wastewater [1–6]. The incorporation of domestic

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wastewater and liquid fraction of kitchen to an aerobic MBR was also tested to develop an integrated decentralized sanitation system [7]. Consideration on improvement of the MBR to achieve zero excess sludge discharge was investigated using the inclined-plate MBR [8,9]. The advantages of the submerged MBR system are that it can reduce space for a wastewater treatment plant due to no requirement of a sedimentation tank and help upgrade treatment plant capacity of a conventional activated sludge. Moreover, it is possible to operate MBR at lower range of dissolved oxygen (DO) concentrations for simultaneous nitrification/denitrification in a long sludge retention time design [10]. Therefore, the MBR can be considered as one of promising treatment technologies for large cities with land limitation. Nevertheless, the problem of membrane fouling is one of the main concerns in running the MBR system that needs an appropriate method to prevent or control membrane fouling phenomena. Here, the inclined tube was introduced as a pretreatment system for the MBR system. The inclined tube was selected as a filter media to sieve or filter large particles and also to remove organic pollutants in the feed wastewater by the biofilm growth on filter media, prior to entering the aerobic degradation zone, using the MBR system. Furthermore, nutrients can also diffuse into the attached biofilm and are further utilized and metabolized by microorganisms in the biofilm.

In this research, a novel inclined tube/biofilm-membrane bioreactor (IT/BF-MBR) system has been developed as a compact on-site wastewater recycling system with less excess sludge wastage and also with the ability of biological nutrient removal purpose. This inclined tube/bioFilm-membrane bioreactor (IT/BF-MBR) system consists of the first-step biofilm compartment (BF1), the second-step biofilm compartment (BF2), then followed by aerobic compartment with the submerged membrane module for the purpose of establishing a compact biological nutrient removal and water reuse system. The two-stage biofilm process can function as a pretreatment step for aerobic MBR and can also function as an inclined tube settler to concentrate sludge at the tank bottom. As a result, sludge digestion under anaerobic condition at the tank bottom can proceed. The necessity of a pretreatment step for the MBR plant was also previously suggested by previous researchers [11,12]. Then, the IT/BF-MBR system can provide a high potential for the treatment and reuse of wastewater from high-rise building in a longer period for system operation. The incorporation of the biofilm process to MBR within the same tank has become more attractive in this study because the membrane can retain all biomass and consequently maintain high SRT condition.

Here, the aim of this present research was to investigate the performance of the IT/BF-MBR system with return sludge recirculation from aerobic compartment to BF1 and BF2 compartment in treating chemical oxygen demand (COD), nutrients (nitrogen and phosphorus) for long term operation. Special attention was given to better understand the mechanisms, behaviors and reliability of the system in treating low-strength sewage. Moreover, the microbial EPS characteristics in terms of main components, such as protein, carbohydrate, and lipid, were also investigated in order to obtain information for prevention of membrane fouling in the long-term operation.

2. Methodology

2.1. Description of the prototype IT/BF-MBR system

The prototype IT/BF-MBR system had a total tank size of $0.6 \times 2.35 \times 2.4$ m. with a total working volume of $3.38\,\mathrm{m}^3$. The reactor was divided into four main compartments as equalization, anoxic, anaerobic, and aerobic compartments. For the working volume of equalization, first-stage biofilm (BF1), second-stage biofilm (BF2) and aerobic compartments were 0.66, 0.68, 0.68, and $1.16\,\mathrm{m}^3$, respectively. The height of inclined tubes installed inside BF1 and BF2 were set to be 0.5 m, which could promote settling zone together with anaerobic condition. The hydraulic retention times for each compartment were 4, 4, 4, and 6.5 h for equalization, BF1, BF2, and aerobic compartments, respectively. A PVDF (polyvinylidene difluoride) hollow fiber microfiltration membrane module having surface area of $6\,\mathrm{m}^2$, and pore size of $0.4\,\mu\mathrm{m}$. was installed inside the aerobic compartment. The MBR unit has a maximum water production capacity of $4\,\mathrm{m}^3/\mathrm{d}$. Nevertheless, in this research, the permeate flow rate was maintained at $3.5\,\mathrm{m}^3/\mathrm{d}$. The cross-flow filtration was achieved by air pump with capacity of 10 L/min. The biomass from the aerobic compartment was initially recirculated to the BF1 and BF2 compartments at the same low recirculation rate 5.0 L/h. At present, the system has been operated without sludge wastage for more than 6 months. The schematic diagram of the IT/BF-MBR is shown in Fig. 1.

2.2. Wastewater

The IT/BF-MBR system received raw wastewater from a 20-floor Mahittaladhibesr Building in Chulalongkorn University, Bangkok at average feed

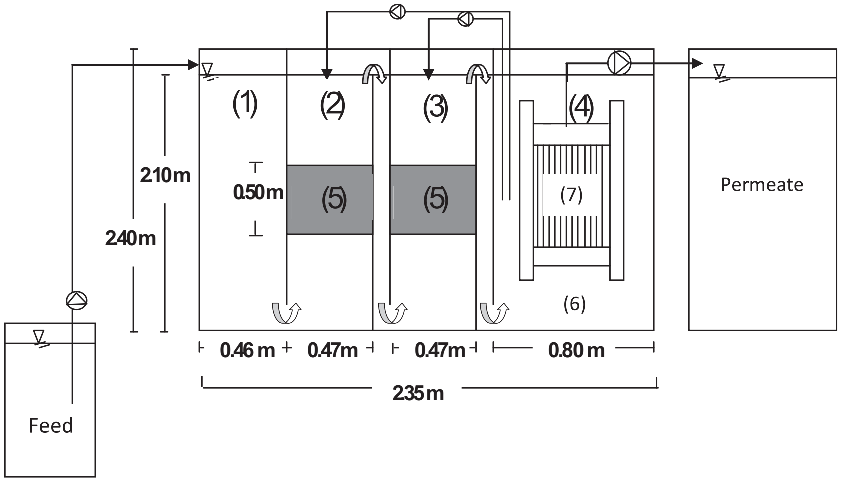


Fig. 1. Schematic diagram of the prototype IT/BF-MBR system. (1) Equalization compartment; (2) first-stage Inclined-tube bioFilm; (BF1); (3) second-stage inclined-tube bioFilm (BF2); (4) aerobic compartment; (5) inclined tube; (6) diffuse aeration equipment; (7) submerged membrane module; ⊳water pump (for feed wastewater and permeate suction); ⇨wastewater flow direction.

flow rate 3.5 m^3/d. Here, the raw wastewater was mainly from toilet and canteen.

2.3. Microbial EPS extraction method

The microbial EPS were extracted using formamide and sodium hydroxide. The carbohydrate content in the EPS was then measured using the Anthrone method (Gaudy, 1962) with glucose as the standard. The protein content in the microbial EPS was determined using the Lowry method with bovine serum albumin as the standard (Lowry et al. 1951). The total lipid content was extracted from the sludge, pretreatment, and then adding methanol/chloroform (1:2, v/v). After 5-min centrifugation, the supernatant was treated with sodium chloride (0.9% w/v). The mixture was centrifuged, and a lipid extract was obtained. Total lipid content after extraction was measured by evaporating the organic solvents and drying in the oven at 45˚C for 15 min and accurately weighing.

2.4. Analytical methods

The DO concentration in the reactor was measured using a DO meter (InPro 6820, Mettler–Toledo), and the pH was monitored using a pH electrode (InPro 3030, Mettler–Toledo). COD was determined according to Standard Method 5220 [13]. Samples were filtered using cellulose acetate syringe filters with pore size of 0.45 μm before the measurements of NO_3–N, NO_2–N, and effluent phosphate in the supernatant. NO_3–N, NO_2–N, and phosphate were measured using ion chromatography, Shimadzu, Prominence HIC-NS. Particle size distribution analysis was performed using the Laser particle size analyzer (Malvern Instrument Ltd).

3. Results and discussion

3.1. pH of the IT/BF-MBR reactor

Fig. 2(a) shows the time course of pH in each compartment (BF1, BF2 and aerobic compartment) of the IT/BF-MBR reactor. The influent pH was found in the range of 4–6, which could promote the activity of acid forming bacteria to degrade large particulate organic matters in the feed wastewater to soluble form of organic matters. Once the feed wastewater entered anaerobic zones of BF1 and BF2, the treated pHs were shifted to approximately 7, implying that denitrification could occur and then stable pH at nearly 7 could be maintained for long run operation. However, a small increase in the effluent pH after aerobic

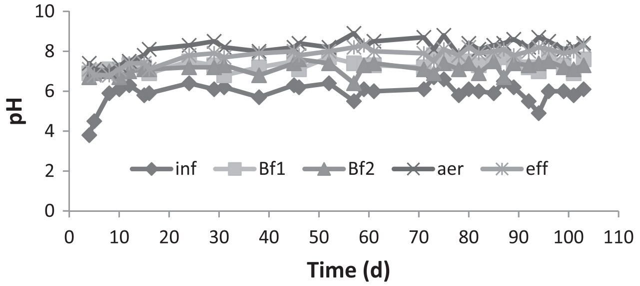


Fig. 2(a). pH variation inside each compartment of the IT/BF-MBR system.

membrane compartment was shifted to nearly 8.0, although nitrification process was found predominant in this compartment, since high nitrate concentration was detected. Therefore, there is no need for pH adjustment in operating the IT/BF-MBR system in treating domestic wastewater.

3.2. Dissolved oxygen

The variations of DO concentrations inside three compartments of the IT/BF-MBR during a long run operation are shown in Fig. 2(b). DO inside the aerobic membrane compartment of the IT/BF-MBR was maintained higher than 2.0 mg/l for providing sufficient nitrification. DO level inside the aerobic membrane compartment was found to be in the range of 2.6–3.2 mg/l. Therefore, dissolved oxygen concentration was not a limiting factor to cause any problem on nitrification and organic removal efficiencies by the IT/BF-MBR system. Also, nitrifying microorganisms could be highly maintained in the system due to sufficient dissolved oxygen and optimum temperature condition at mesophilic temperature range. However, further system improvement by lowering DO concentrations in BF1 and BF2 compartments is suggested in order to promote more complete anaerobic and anoxic zones inside the IT/BF-MBR system, which will promote denitrification activity and also enhanced biological phosphorus removal (EBPR) activity in BF1 and BF2 compartments. The possible solution can be done by either increasing the feed flow rate to the system or reducing the sludge recirculation rate from aerobic compartment to the BF1 and BF2 compartments.

3.3. Organic removal performance

Variation of influent COD concentration from 100 to 130 mg/l did not affect the performance of the IT/BF-MBR system in treating organic carbon from wastewater as illustrated in Fig. 3(a). Since the COD concentrations in the effluent were always lower than 10 mg/l after 45 days, together with the COD removal efficiencies were above than 90% suggesting that stable treatment performance of the system could be achieved. These data indicated that the system could provide a consistent high efficiency of COD removal. The advantages of the IT/BF-MBR system are the overall combination of a membrane separation unit and biochemical activity of the biofilm and also suspended growth biomass in the IT/BF-MBR process. Also, the influent characteristics show that the wastewater sometimes contained high amounts of colloidal organic matters that can deteriorate treatment performance of a conventional activated sludge process. Nevertheless, this can be considered to cause less problem for stable treatment-performance by using the IT/BF-MBR system. The important aspect concerns the operation concept regarding the inclined-tube biofilter as a pretreatment step is that the biofilter helps sieve and filter large colloidal particle in BF1 and further degrade organic matters in the second-stage biofilter (BF2) before entering the aerobic membrane compartment, as more than 50% of total COD in the feed wastewater could be apparently reduced in the BF2 tank. As a result, colloidal and soluble organic matters were removed before entering the aerobic membrane compartment. Then, the soluble COD was further removed in the following aerobic compartment by high biomass of aerobic microorganisms that were retained by the membrane unit. Final effluent was proved to have excellent COD concentration lower than 10 mg/L, which can be further reused for building application.

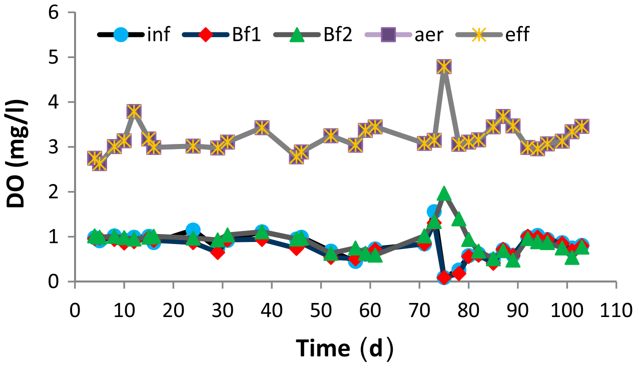


Fig. 2(b). DO concentration in each compartment of the IT/BF-MBR reactor.

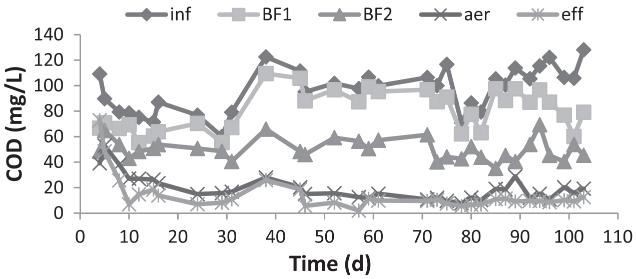


Fig. 3(a). Organic removal in each compartment of the IT/BF-MBR reactor.

3.4. Phosphorus removal performance

During the whole operation period for the IT/BF-MBR, changes in concentration of total phosphorus in the influent, BF1 and BF2 compartments,

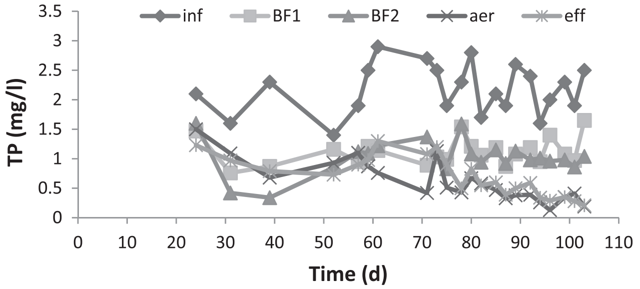


Fig. 3(b). Changes in phosphorus concentration in each compartment of the IT/BF-MBR reactor.

aerobic compartment, and effluent are shown in Fig. 3 (b). Total phosphorus concentration in the feed wastewater could be found in the range of 1.5–3.0 mgP/L. Significant amount of phosphorus removal could be achieved with the IT/BF-MBR system. The average phosphorus concentration in the effluent from BF2 was approximately 1.0 mg/L and then lowered in the aerobic compartment to 0.3 mg/L. Phosphorus removal efficiency was found to be 90.2%. The main phosphorus-removing process expected was incorporation into the biomass inside the IT/BF-MBR system. As the phosphorus release was not observed in the BF1 and BF2 compartments, EBPR was insignificant.

3.5. Nitrogen removal performance

Fig. 4 presents the variation of NH_4^+–N, NO_2^-–N, and NO_3–N concentrations in the IT/BF-MBR system during the whole experiment. The influent nitrogen mainly was in the form of soluble ammonia and then changed into nitrate nitrogen in the aerobic compartment due to a good performance of nitrification: pH value of the aerobic compartment was 8.0 beyond the optimum range of ammonia-oxidizing bacteria and also nitrite-oxidizing bacteria. It is shown in Fig. 4 that a significant reduction in NH_4^+–N concentration was obtained by the IT/BF-MBR system. Nitrogen was removed from the wastewater through incorporation in biomass (BF1 and BF2 compartments) and nitrification (aerobic compartment).

This significant reduction in NH_4^+–N concentration from 12 mg/L to approximately 3 mg/L could be attributed to biomass metabolism of the attached growth inside the BF2 compartment and further ammonia reduction could be achieved in the aerobic membrane compartment due to nitrification activity, which was very stable. The very stable nitrification was resulted from sufficient DO, which was in a range of 2.6–4.0 mg/l. However, high amount of nitrate concentration remained which implying that the denitrification was not accomplished completely due to low rate of sludge return from aerobic compartment to BF1 compartment.

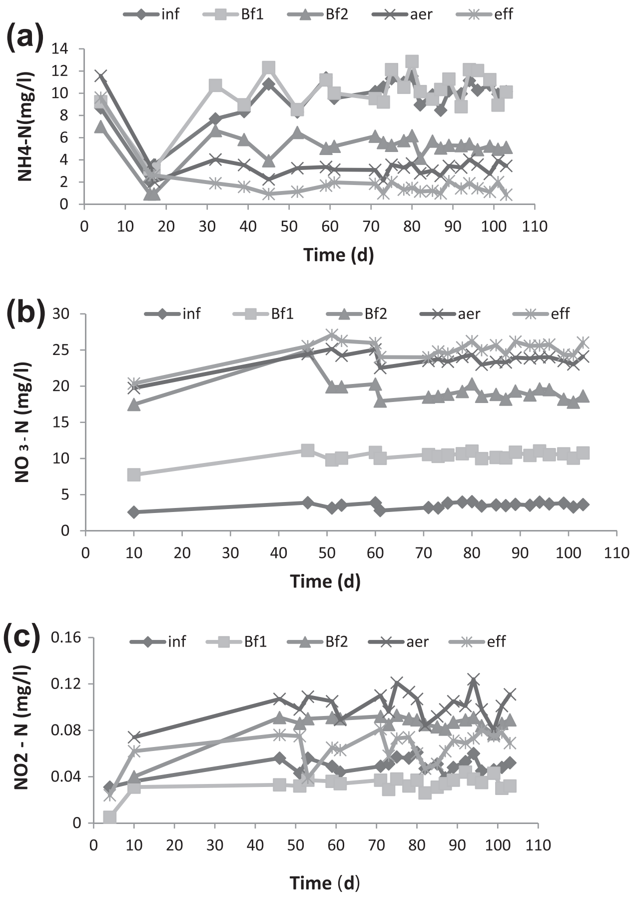
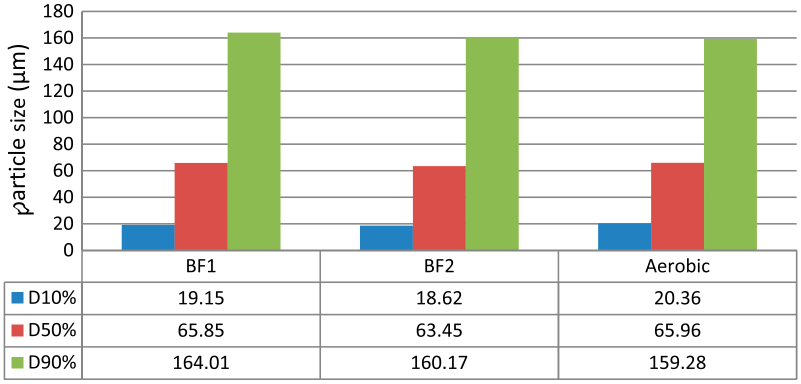


Fig. 4. Change in nitrogen concentrations in each compartment of the IT/BF-MBR reactor; (a) ammonia, (b) nitrate, and (c) nitrite nitrogen.

Moreover, the IT/BF-MBR system can maintain high concentration of nitrifiers, and therefore, it could achieve a high performance of nitrification efficiency. Nevertheless, the removal of total nitrogen in the IT/BF-MBR system was still limited due to insufficient sludge recirculation rate (only 50% in this study) and also insufficient carbon-to-nitrate nitrogen ratio (C/NO_3^-–N) in the system (less than 5:1). The above-mentioned discussion provides a measure to improve performance of the IT/BF-MBR system in terms of total nitrogen removal in the next operation.

3.6. Particle size distribution inside the IT/BF-MBR reactor

Particle size distribution of the particulate matters obtained from each compartment (BF1, BF2, and aerobic compartment) of the IT/BF-MBR reactor is shown in Fig. 5. It was found that total particulate matters in



	BF1	BF2	Aerobic
🟦 D10%	19.15	18.62	20.36
🟥 D50%	65.85	63.45	65.96
🟩 D90%	164.01	160.17	159.28

Fig. 5. Particle size distribution inside the IT/BF-MBR reactor.

BF1, BF2 and aerobic compartments had the average sizes of D50% at 65.85, 63.45, and 65.96 µm, respectively. With the size range distribution from D10 to D90%, overall particulate matters found in the IT/BF-MBR reactor had variation in size range from 19.15 to 164.01 µm. It means that the particle size of particulate matters is larger than the pore size of membrane (0.4 µm), so these particulate matters can be significantly retained inside the system and further biodegraded by microorganisms in the IT/BF-MBR reactor.

3.7. Characterization of the microbial EPS in the IT/BF-MBR system

Microbial EPS (extracellular polymeric substances) are biopolymers mainly consisting of polysaccharides, proteins, nucleic acid, and lipids [14] in either form sludge flocs or biofilms. These components in microbial EPS can promote membrane fouling in long-term system operation as confirmed by atomic force microscopy observation [15]. Table 1 summarized the quantities of EPS extracted from the biomass in BF1, BF2, and aerobic compartment. The results for biomass indicated that the collected EPS was primary composed of carbohydrates, proteins, and lipids.

Each gram of MLSS in the sludge from BF1 compartment contained 7.475 ± 0.186 mg proteins, 7.475 ± 0.186 mg carbohydrates, and 120.056 ± 3.562 mg of lipids. For BF2 compartment, each gram of MLSS in the sludge contained 0.318 ± 0.019 mg proteins, 5.685 ± 0.546 mg carbohydrates, and 119.90 ± 7.517 mg of lipids. Also, the aerobic compartment with the submerged membrane installation, the sludge content per each gram of MLSS contained 0.356 ± 0.012 mg proteins, 7.129 ± 0.058 mg carbohydrates, and 119.897 ± 17.07 mg of lipids. Therefore, the main microbial EPS inside the system was carbohydrate and lipid, rather than protein. These EPS content could result in membrane fouling in long-run operation.

Table 1
EPS component of sludge from each compartment inside The IT/BF-MBR reactor

Compartment	Carbohydrate (g/gMLSS)	Protein (g/gMLSS)	Lipid (g/gMLSS)
BF 1	7.475 ± 0.186	0.396 ± 0.021	120.056 ± 3.562
BF 2	5.685 ± 0.546	0.318 ± 0.019	119.90 ± 7.517
Aerobic	7.129 ± 0.058	0.356 ± 0.012	119.897 ± 17.07

3.8. Microscopic examination of sludge in the IT/BF-MBR reactor by the phase contrast method for analysis of cell morphologies

Fig. 6(a) demonstrated microbial complexity of an MBR sludge by gram staining. Also, Fig. 6(b) showed a complex microbial cluster of Gram-negative filamentous and coccobacilli bacteria or diplococci-arranged cluster dominate in the sludge. Gram-negative tetrad-arranged cocci bacteria or G-bacteria were observed according to their characteristic arrangement of four cells in the sludge as shown in Fig. 6(c). G-bacteria have been though to effectively assimilate soluble organic matters in wastewater, and therefore, these types of bacteria are one of the dominant populations in microbial community inside the IT/BF-MBR system under mesophilic temperature range condition. Fig. 6 (d) illustrates Gram-positive bacilli and filamentous Gram-negative bacteria within the sludge among the complex microbial structure. The predominant of Gram negative bacteria found in the MBR system were also reported [16,17].

3.9. Potential wastewater reuse application

The potential wastewater reuse application after treatment with the IT/BF-MBR system was evaluated

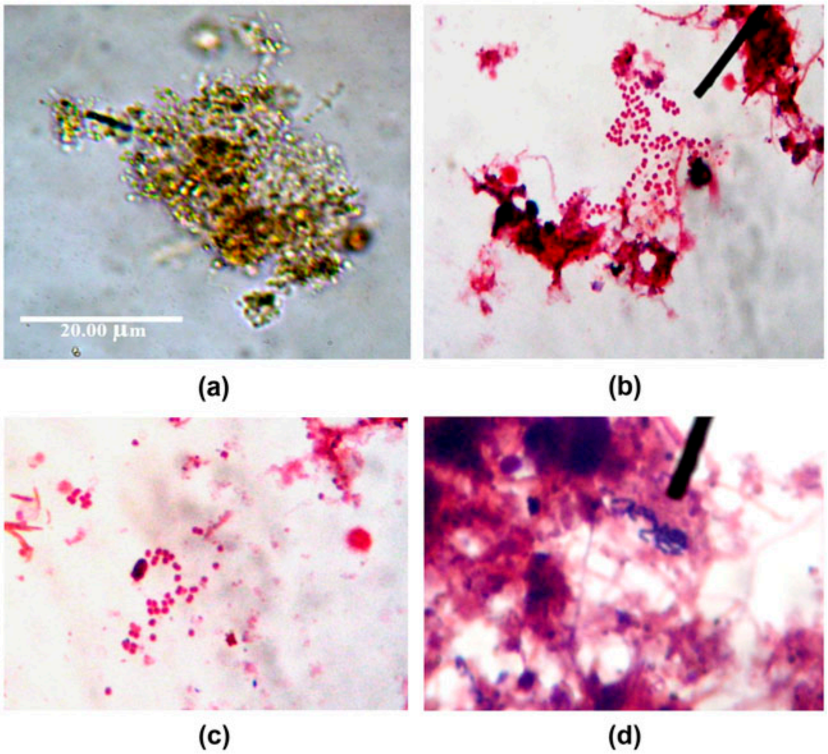


Fig. 6. Microbial complexity and cell morphology of biomass inside the IT/BF-MBR reactor. (a) Microbial floc characteristics inside IT/BF-MBR; (b) microbial cluster of Gram negative filamentous and coccobacilli bacteria; (c) Gram negative tetrad-arranged cocci bacteria, and (d) Gram positive bacilli and filamentous or "G" bacteria Gram negative bacteria within the sludge.

here by comparing the treated effluent quality with the Japanese Ministry of Land, Infrastructure and Transport's Reuse water quality criteria, 2005 for building application. The wastewater reuse application for toilet flushing and garden watering has been highly concerned here due to large amount of water demand for many high-rise buildings. From Table 2, these data show that the effluent quality from the IT/BF-MBR system in terms of pH, turbidity, odor, appearance, and *E. coli* could comply with the reuse water quality criteria that are required for toilet flushing and garden watering. Therefore, the IT/BF-MBR can be considered as an alternative compact decentralized wastewater treatment system for high-rise building wastewater reuse purpose.

Table 2
Comparison of effluent quality from the IT/BF-MBR reactor with Japanese Ministry of Land, Infrastructure and Transport's Reuse water quality criteria, 2005

Parameters	Effluent quality	Wastewater reuse criteria	
		Toilet flushing	Garden watering
pH	7.5–8.3	5.8–8.6	5.8–8.6
Turbidity (NTU)	0–0.1	Less than 2	Less than 2
Odor	Not unpleasant	Not unpleasant	Not unpleasant
Appearance	Not unpleasant	Not unpleasant	Not unpleasant
E. coli	Not detected	Not detected	Not detected

4. Conclusions

The IT/BF-MBR system could perform as a single compact reactor for high-rise building wastewater treatment without sludge wastage in long-term operation. The system could achieve high efficiencies above 99% in terms of turbidity and SS removal. Stable treatment efficiencies of above 90% removal for COD, ammonia nitrogen, and total phosphorus could be achieved in long-term operation of the IT/BF-MBR system. Moreover, very stable nitrification activity was observed in the aerobic MBR compartment. Furthermore, water quality of the treated effluent could comply with the standard of reuse water quality for toilet-flushing and garden-watering purposes.

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