Environmental Science and Pollution Research (2019) 26:25883–25897
https://doi.org/10.1007/s11356-019-05746-2

RESEARCH ARTICLE

Performance analysis and life cycle greenhouse gas emission assessment of an integrated gravitational-flow wastewater treatment system for rural areas

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Received: 12 February 2019 / Accepted: 12 June 2019 / Published online: 4 July 2019

Abstract

Due to the lack of appropriate wastewater treatment facility in rural areas, the discharging of wastewater without sufficient treatment results in many environmental issues and negative impact on the local economy. In this study, a novel integrated gravitational-flow wastewater treatment system (IGWTS) for treating domestic wastewater in rural areas was developed and evaluated. As the core module of IGWTS, the multi-soil-layering (MSL) system showed good performances for removing organic matters and nutrients in lab-scale experiments. Aeration was found to be the dominant positive factor for contaminant removal in factorial analysis, while bottom submersion had the most negative effect. Based on the critical operational factors obtained from lab-scale tests, the full-scale IGWTS consisting of multifunctional anaerobic tank (MFAT), MSL, and subsurface flow constructed wetland (SFCW) was designed, constructed, and operated successfully in the field application. The final effluent concentrations of COD, BOD_5, TP, NH_3-N, and TN reached 22.0, 8.0, 0.3, 4.0, and 11.0 mg/L, with removal rates of 92, 93, 92, 86, and 76%, respectively. The feasibility of IGWTS was also quantitatively evaluated from the perspectives of resource consumption, economic costs, water environment impact, and life cycle greenhouse gas (GHG) emissions. IGWTS has been proved to be a sound approach to mitigate GHG emissions compared with centralized wastewater treatment plant. It can also be featured as an eco-friendly technology to improve rural water environment, and an economic scenario with low construction and operation costs.

Keywords Multi-soil-layering (MSL) system · IGWTS · Domestic wastewater treatment · Economic analysis · Life cycle assessment (LCA) · Greenhouse gas (GHG) emissions

Explored the effects of operational factors on the performances of lab-scale MSL.
Designed an integrated gravitational-flow wastewater treatment system.
Assessed the resources consumption and economic superiority of integrated system.
Analyzed the GHG emission of integrated system based on LCA method.

Responsible editor: Philippe Loubet

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11356-019-05746-2) contains supplementary material, which is available to authorized users.

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Introduction

The wastewater management in rural areas has been often ignored in developing countries (Herrera-Melian et al. 2018; Liu et al. 2018; Zhou et al. 2019). Due to the lack of appropriate wastewater treatment facility, the discharging of wastewater without sufficient treatment results in the deterioration of water environment quality, long-term black and odorous water, and negative impact on the local economy (An et al. 2016; Latrach et al. 2018). The ideal wastewater treatment strategy for rural areas should consider not only the treatment efficiency but also resource recovery and low investment (Gu et al. 2017; Kalbar et al. 2012). In particular, there is also a concern of clean energy and it is expected to use some technologies with less energy consumption and greenhouse gas (GHG) emissions (Wakeel et al. 2016; You et al. 2011). Traditional large-scale centralized wastewater treatment facilities are not suitable for small communities, where the support of infrastructure, capital, and skilled personnel is usually limited (Fan et al. 2017; Farrow et al. 2018).

For rural areas, decentralized land-based wastewater treatment technologies are ideal solutions for pollution control (An et al. 2016; Hu et al., 2018; Machado et al. 2007). In previous efforts, decentralized wastewater treatment technologies such as constructed wetland (CW) system with good treatment performance and landscape ecological effects have been reported (de la Varga et al. 2015; Lutterbeck et al. 2017). Besides them, the multi-soil-layering (MSL) system firstly proposed by Wakatsuki (1993) is also an environment- and economy-friendly alternative for decentralized wastewater treatment based on lab and field studies (Guan et al. 2012; Zhang et al. 2015). Each technology has its own advantage and application requirement. However, it should be noted that there are different requirements which can hardly be met by single treatment approach in practical implementation. It is of interest to integrate different decentralized wastewater treatment technologies, which can not only achieve the higher treatment efficiency but also meet the strict requirements in terms of system construction, operation, and maintenance. Currently, the related studies are limited and many important processes in the integrated treatment are still unclear.

Low-carbon green property and water environment protection are important criteria for the development of new wastewater treatment technology in rural areas (Shi et al. 2013; Wang and Banzhaf 2018; Xu et al., 2018). Life cycle assessment (LCA) enables to quantificationally evaluate the potential environmental impacts of a studied system or a product within the scope of life cycle, and facilitate its favorable aspects from a holistic perspective (Kamble et al. 2017; Piao et al. 2016). For wastewater treatment technologies, GHG emissions can be considered as the most important indicator related to low-carbon green property through the quantified calculation during the entire life cycle (Blanco et al. 2018; Morrison et al. 2016). In addition, freshwater eutrophication potential (FEP) and freshwater aquatic ecotoxicity potential (FAETP) are the most two concerned indexes in connection with water environment impact assessment (Barba-Brioso et al. 2010; Xin et al. 2017), which can be evaluated based on parameters of final effluent. However, few quantitative evaluations have been conducted to investigate the performance of integrated wastewater treatment technologies, especially for its practical application in rural areas.

In this study, therefore, a novel integrated gravitational-flow wastewater treatment system (IGWTS) will be developed and evaluated. The detailed objectives are to (i) study the significant effects of environmental factors and their interactions on treatment performance of MSL system based on factorial analysis, (ii) design an integrated land-based wastewater treatment system and evaluate its performance in the field application and potential impact of final effluent on water environment, (iii) analyze the economic feasibility of IGWTS for its application through the inventory details about material usage and energy consumption, and (iv) investigate the life cycle GHG emissions of the developed system in rural areas. The results will be helpful for achieving effective and sustainable decentralized wastewater treatment technology in rural areas.

Materials and methods

Lab-scale MSL system

The schematic configuration and construction of lab-scale MSL system is shown in Fig. 1. The system consists of soil mixture blocks (SMBs) and permeable layers (PLs), with the details shown in Supplementary Material. Due to the unique characteristics of MSL system in structure, SMBs and PLs can work as anaerobic zone and aerobic zone, respectively (Sato et al. 2011; Song et al. 2018). The synthetic wastewater was used as influent according to the real domestic wastewater quality in rural areas (Jin et al. 2014; Reichwaldt et al. 2017). The composition of synthetic wastewater is shown in Supplementary Material. The HLR in experiment was 400 L/(m^2 day), and the wastewater was continuously pumped into MSL system using ZT600-1J peristaltic pumps (Longer Co., Ltd., China).

Bottom submersion in lab-scale MSL system was simulated by submerging the lowermost SMBs under the water outlet position, since the stagnant wastewater in the bottom of MSL system may impact the treatment performance of full-scale application. The microthermal activated sludge (MAS) from wastewater digester (Bio-Form Co., Ltd., Foshan, China) was cultivated and inoculated as extraneous microbial amendment in MSL system, and the detailed operation procedures are shown in Supplementary Material. To study the effect of aeration on treatment performance of MSL system, uninterrupted air supplement was provided by aeration pumps at a rate of 12,000 L/(m^3 day). The experiments were carried out using a 2-level factorial design including three factors, including bottom submersion (factor A), microbial amendment (factor B), and aeration (factor C). The

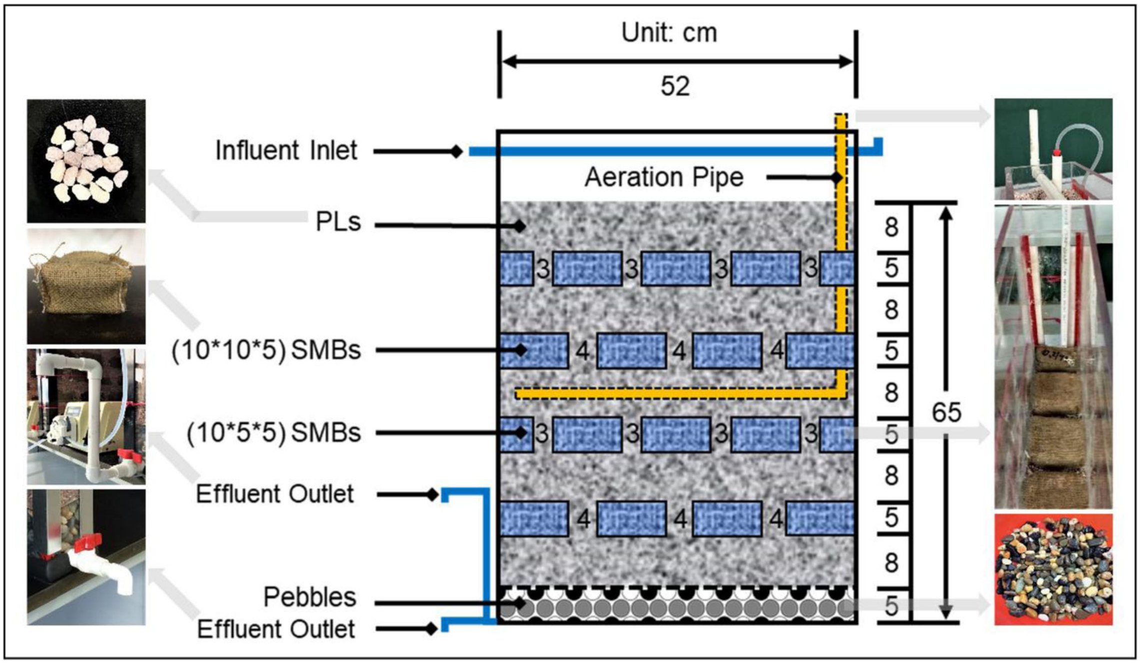

Fig. 1 The schematic configuration of lab-scale MSL system

factors in 2-level factorial design is shown in Fig. S1. Six parameters, including chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD_5), total phosphorus (TP), ammonia nitrogen (NH_3-N), total nitrogen (TN), and dissolved oxygen (DO) of effluent were monitored termly.

Field application of IGWTS

The developed IGWTS consisted of a grill pool (GP), a multi-functional anaerobic tank (MFAT), a multi-soil-layering (MSL) system, and a subsurface flow constructed wetland (SFCW) in sequence was applied in a Youth Inn at Linyi, Shandong, China. The inn was within a farmhouse resort about rural tourism. Rural tourism can enhance the income of local communities, while they can also impact environmental quality and ecology resilience in rural areas (Sasidharan et al. 2002; Lin et al. 2018). Previously, the domestic wastewater from the Youth Inn was directly released to adjacent watercourses or lands without treatment. The full-scale IGWTS was built and operated to minimize the negative effects of discharging raw wastewater, with a focus on reducing organic pollution and eutrophication. The designed water flow of IGWTS for household application is 5 m^3/day, with average concentrations of COD 4.03 kg/day, BOD_5 2.22 kg/day, TP 0.03 kg/day, NH_3-N 0.23 kg/day, and TN 0.37 kg/day.

Water environment impact assessment

Although the effluent was discharged after step-by-step treatment of each module in IGWTS, the potential impacts of eutrophication and toxicity on water environment should not be neglected. FEP and FAETP are considered as the most two concerned indexes in connection with water environment impact assessment, which can be evaluated through comprehensive trophic level index (CTLI) and toxicity criteria of nitrite nitrogen (TC-NO_3^-), respectively (Barba-Brioso et al. 2010; Camargo and Alonso 2006). In this study, CTLI will be quantified on the basis of the parameters of final effluent, and the concentration of NO_3^- in final effluent has been compared with chronic toxicity criteria of NO_3^- (CTC-NO_3^-) and acute toxicity criteria of NO_3^- (ATC-NO_3^-) to aquatic organisms (Leeuwen and Vermeire 2007; USEPA 1985), detailed calculations are shown in Supplementary Material.

Life cycle framework for GHG emission assessment

The standardized LCA framework was employed for quantitative analysis of potential impacts (Bastianoni et al. 2014; Ledon et al. 2017). For the IGWTS, GHG emission is considered as the most important indicator related to low-carbon green property. Fig. 2 shows the system boundary for GHG emission assessment of the IGWTS. Due to this small-scale and above-ground system, large machineries such as excavator and bulldozer were not involved and were substituted by manual labor in construction and operation. The productive processes of the construction materials and packing media as well as their transportation were not considered. The initial stage of life cycle was defined as the input of materials, energy, and labor force at the beginning of construction. From the perspective of long term operation, processes such as building material reuse, fertile soil recycling, and landscape renovation linked to demolition of the treatment system could be out of system boundary, since it is generally negligible when

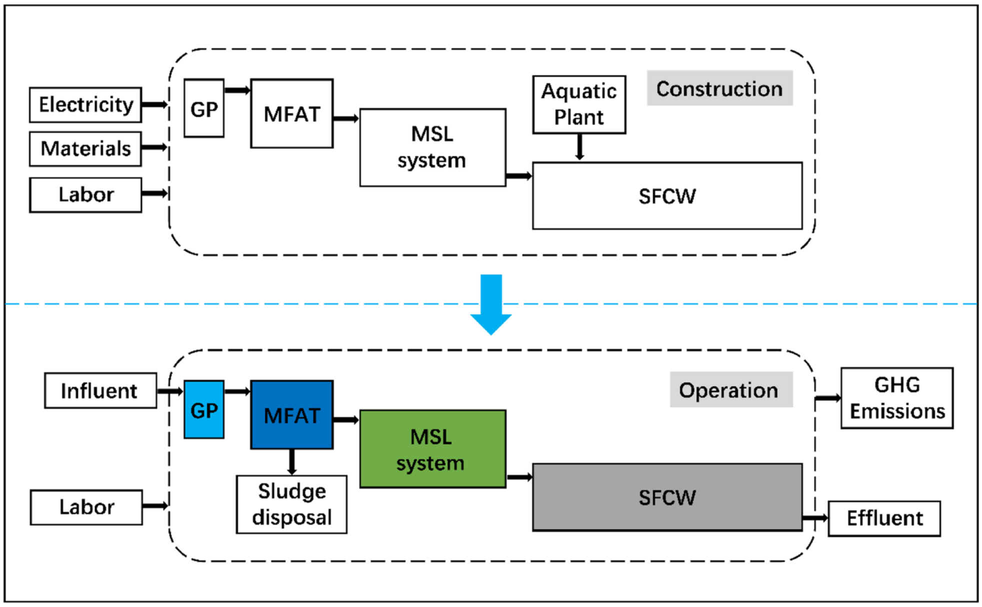

Fig. 2 System boundary for GHG emission assessment of the IGWTS related to construction and operation

compared with the construction and operation phases (Wang et al. 2012). In addition, sludge drying for fertilizer was considered as routine maintenance of operational MFAT within system boundary. Thus, this case study mainly focused on the phases from construction to operation. For life cycle GHG emission investigation, all inputs, outputs, and analytical results could be quantified relative to 1 m^3 of water. The life cycle of IGWTS for calculation was 10 years, with the detailed assessment process shown in Supplementary Material.

Inventory management and EFA

In this study, inventory mainly consisted of material input, energy consumption, costs, and life cycle GHG emissions. Economic feasibility analysis of wastewater treatment was conducted to address the economic concern of rural areas (Mao et al. 2015). The costs of IGWTS mainly included the investment for infrastructure construction and operation during life cycle. The cost of materials and electricity consumption during construction period were acquired from the project inspection report. The energy consumption within the system boundary was mainly related to the electricity consumption for on-site working such as light illumination, since the construction and installation of this small-scale treatment system were carried out by manual manipulation. Light illumination would be necessary and only operated at the dusk period to legally protect the workers' safety, and also can be used as a safety warning to surrounding villagers. In addition, the expenditure for safety signs was also considered. The operational costs for IGWTS were associated with sludge disposal and aquatic plant cultivation, which would be handled manually without any energy consumption during the operation of IGWTS.

Analytical methods

The physicochemical properties of wastewater in both lab-scale experiment and on-site IGWTS were measured according to the Standard Methods for the Examination of Water and Wastewater (APHA 2005). The detail requirements are shown in Supplementary Material. The factorial design of experiment and statistical analysis of experimental data were conducted using Design Expert 8.0.5 (Stat-Ease Inc., USA). The OriginPro 2016 software (OriginLab Corporation, USA) was used for drafting.

Results and discussion

Performance of lab-scale MSL system

Contaminants removal

DO is the most important parameter to indicate which condition in MSL system, aerobic or anaerobic (An et al. 2016). DO variation is shown in Fig. 3. The detailed results of DO concentration are shown in Supplementary Material. The removal rates of COD, BOD_5, TP, NH_3-N, and TN are also shown in Fig. 3. Microbiological degradation played an important role in removing organic matters from domestic wastewater (Chen et al. 2017). The organic matters were easily trapped in SMBs and zeolite particles which had large amount of pore spaces and surface areas to provide habitats for various microorganisms (Latrach et al. 2018; Zhang et al. 2015). The microorganisms within MSL system could adapt to the system and proliferate in the oxygenated environment, which also helped to reduce clogging risk and maintain high water permeability in

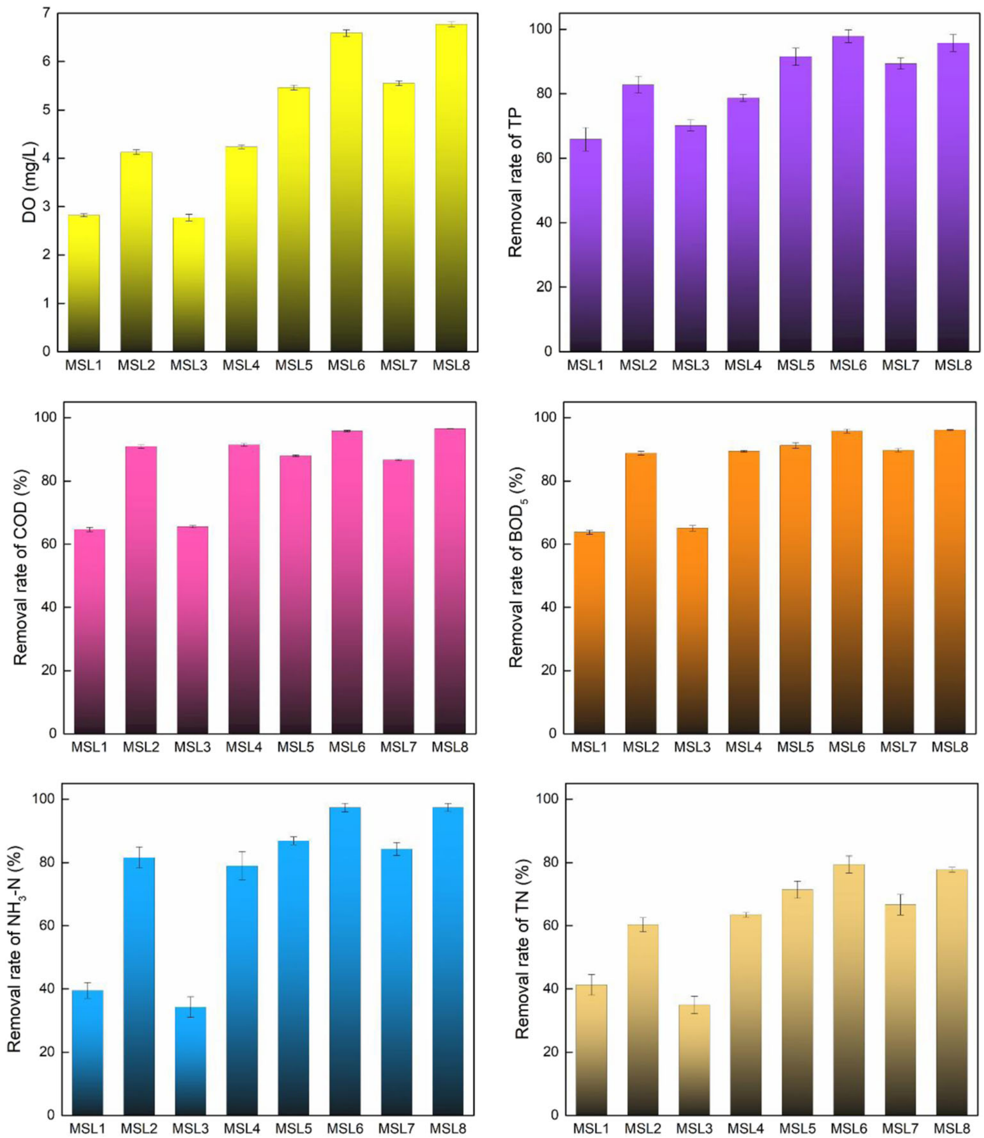

Fig. 3 DO variation and removal rates of COD, BOD_5, TP, NH_3-N, and TN from domestic wastewater through MSL system

MSL system (Boonsook et al. 2003). The decomposition of organic matters was enhanced with the growth of microorganisms in system. What is more, filtration and adsorption processes also contributed to the removal of organic matters, especially at the initial stage of operation (An et al. 2016; Wang et al. 2018). The detailed results related to the removal rates of COD and BOD_5 are shown in Supplementary Material.

When wastewater went through PLs, phosphorus could be fixed via the formation of chemical precipitate ($FePO_4$). Both dissociative and adsorbed phosphates were chemically combined with Fe^{3+} or Fe hydroxides (Fe $(OH)_3$) (Ho and Wang 2015). Efficient TP removal mainly depended on Fe ion production and flow diffusion in MSL system (Guan et al. 2012). Additionally, TP could also be removed from wastewater through filtration and adsorption processes. Sufficient oxygen facilitated the oxidization of Fe^{2+} to Fe^{3+}, leading to a higher adsorption rate of phosphate by soil particles (Boonsook et al. 2003). Flow distribution would influence the contact time between wastewater and filling media, then disturb the transformation from Fe to Fe^{2+} or Fe^{3+}. The detailed results related to the removal rate of TP is shown in Supplementary Material.

Biological transformation and degradation were two dominant mechanisms in nitrogen treatment processes (Pelissari et al. 2017). The cation exchange capability (CEC) of zeolites in PLs and physical adsorption on materials also played important roles in the removal of NH_3-N during the start-up period (An et al. 2016). However, it would become less important when approaching the saturation of CEC. The more effective biotransformation of nitrifying bacteria, the higher removal rate of NH_3-N. The results showed that the process of transforming NH_3-N was restrained under anaerobic condition. In MSL system, both aerobic environment (aeration) and anaerobic environment (bottom submersion) made contributions to TN removal, and they were related to nitrification and denitrification mechanisms, respectively. The detailed results related to the nitrogen removal is shown in Supplementary Material. Overall, in the lab-scale experiment, MSL system showed the satisfying performances under different operating conditions, which could be attributed to complicated mechanisms and processes of contaminant removal in MSL.

Factorial analyses

Factorial analysis was carried out to reveal the significant factors and their interactive effects on the treatment performance of MSL system (Shen et al. 2017). Fig. S2 shows the normal probability plots of residuals for 6 indexes, in which points were approximately on the straight line, indicating the reliable normal distribution of experiment data (Chen et al. 2019; Huang et al. 2018). The results of analysis of variance (ANOVA) for 6 responses, and all the main effects and interactions are shown in Tables S1 to S6. The "statistical *P* values" were much less than 0.05, which implied the models were significant (He et al. 2018). The normal probability plots of effects and interactions for MSL systems are shown in Fig. 4. The farther the distance between points and dividing line indicates the more significant effects of factors or interactions (Xin et al. 2016). In addition, the normal probability plot not only visualizes positive or negative effects of factors with different color but arranges all effects in decreasing order of distances to show their significant levels.

The presence of factor B-microbial amendment did not exhibit obvious advantages due to its competition for oxygen and nutrients with indigenous microorganisms in soil. The results showed that factor A-bottom submersion and factor C-aeration had the most negative and positive effects, respectively. In MSL system, factor C-aeration played a positive role in supplying oxygen to balance the DO consumption. Sufficient oxygen supply was favorable for biodegradation and chemical oxidation to remove contaminants (Luanmanee et al. 2001). Aeration can provide oxygenated environment for nitrifying bacteria and facilitate the transformation of NH_3-N into NO_3^--N. On the contrary, independent factor A-bottom submersion had the adverse effect on biodegradation and presented negative effect on contaminant removal.

As shown in Fig. 4, the interaction of A*C exhibits the positive effect on contaminant removal. Thus, the interactive effects of factor A-bottom submersion and factor C-aeration on all responses were paid great attention. In Fig. S3, two approximately parallel lines indicated almost no interaction effect between these two factors. For example, compared with independent factor A-bottom submersion, factor C-aeration obviously increased the DO concentration in MSL system. However, lines related to the interaction of A*C presented almost no slope variation from their low level to high level, which indicated no interactive effect on DO. On the contrary, the different slopes of two lines implied that there was an interactive effect between these two factors, such as the interactive effects of A*C on the removal of COD, BOD_5, TP, NH_3-N, and TN. Although there was slightly negative slope of interactive line from low level to high level of factors, the involvement of aeration significantly improved the removal of organic matters because oxygen supply was favorable for biodegradation in MSL system. In addition, the removal of organic matters in stagnant water zone was facilitated by aeration as well. The interactive effect of A*C on TP removal was benefited from the aeration and large storage space of submerged zones for retaining final insoluble ferric phosphate. The best performance of TP removal was associated with the aeration at its high level without bottom submersion. Regional anaerobic environment due to bottom submersion in MSL system resulted in inefficient nitrification and the low removal performances of NH_3-N and TN. In addition, the competition for oxygen and nutrients between microbial amendment and nitrifying bacteria would also aggravate this negative effect. However, the favorable oxygenated environment could efficiently mitigate this adverse condition in MSL system even in the presence of bottom submersion.

Design of the MSL-based IGWTS

A novel IGWTS was designed and built in this study. The schematic configuration of IGWTS and the operation of on-site application are shown in Fig. 5. Before IGWTS, a pretreatment tank was used to remove large insoluble particles and debris from influent. Engineered slope from high to low was used in IGWTS, which provided a hydraulic gradient for driving wastewater flow by gravity. The basic setting and design parameters of each subsystem are shown in Table S7.

Treatment modules of IGWTS

Primary treatment in MFAT The rural domestic wastewater often contains high levels of organic substances, fats, and oils, which will increase the difficulty of biodegradation and risk of clogging in land-based wastewater treatment systems (An et al. 2016; Zhang et al. 2015). It is hard to use MSL system or SFCW alone to achieve all treatment requirements. The primary treatment of IGWTS was conducted by MFAT, which was composed of an anaerobic fixed film unit, a fat and oil removal unit, and a drop aeration unit. A set of pensile carriers was installed in the anaerobic fixed film unit to provide large surface areas for the attachment and growth of microorganisms, which could enhance microbial activities and avoid the loss of functional microorganisms. The refractory macromolecular organic matters of domestic wastewater can be transformed to biodegradable organic matters (volatile fatty acids) through hydrolysis and acidification under anaerobic condition (Li et al. 2018). Then, the volatile fatty acids could be further degraded into inorganic gas molecules such as CH_4, CO_2, H_2, and etc. Meanwhile, TP could be assimilated by phosphorus-accumulating bacteria in MFAT under anaerobic condition (Sun et al. 2015). The decrease of TN concentration

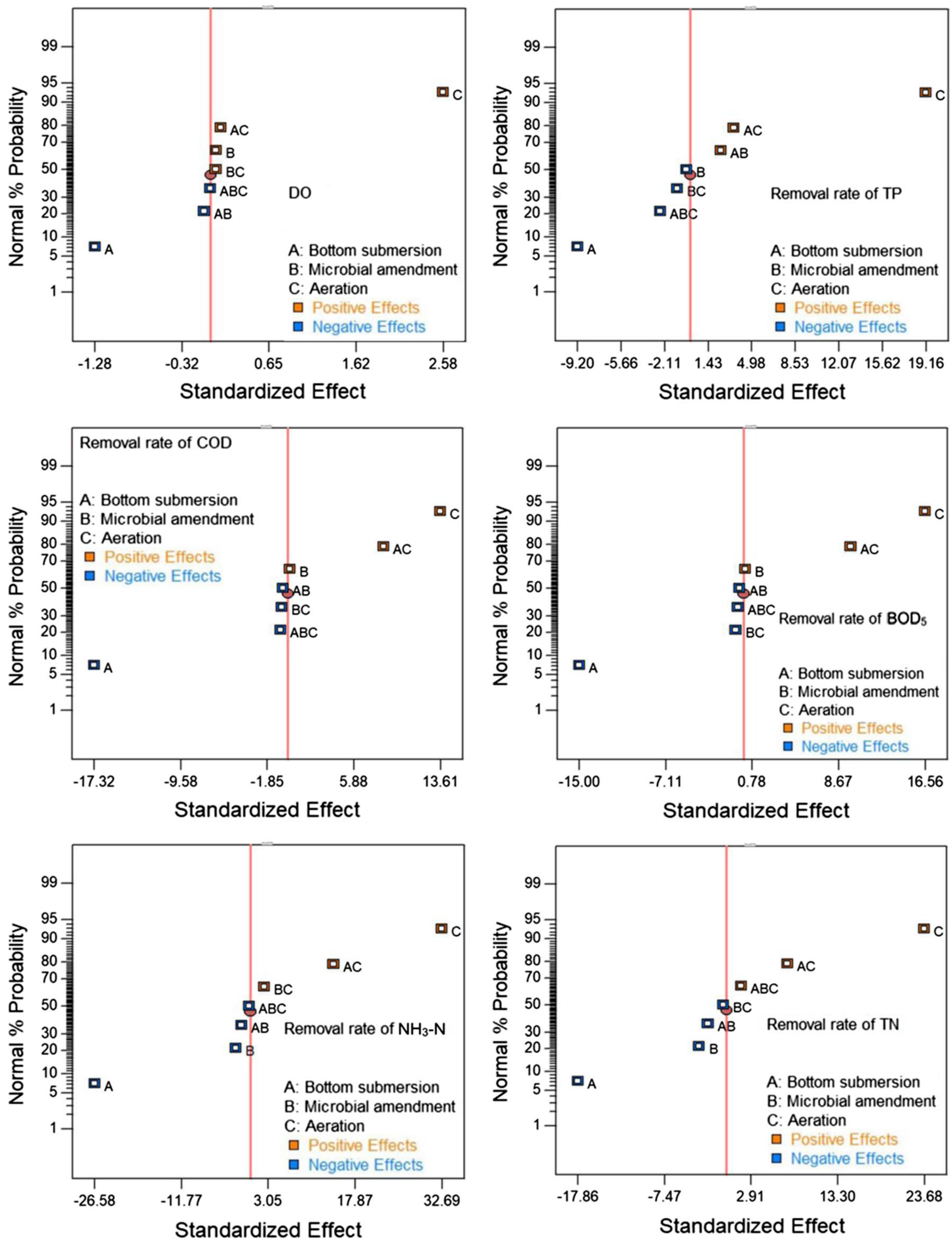

Fig. 4 Normal probability plot of effects and interactions on DO, and removal rates of COD, BOD_5, TP, NH_3-N, and TN

in MFAT could mainly be attributed to anaerobic ammonia oxidation and denitrification processes (Zubrowska-Sudol and Walczak 2014). In addition, fats and oils in wastewater could be removed in MFAT based on its special design of water pipeline and baffle, which would facilitate the separation of liquid with different densities. MFAT could improve the biodegradability of raw wastewater and reduce the nutrient loads for the following MSL system. According to the experimental results of our lab-scale MSL systems, aeration was the most positive independent factor for increasing treatment efficiency. Therefore, reoxygenation of wastewater in the end of MFAT was carried out using the semi-open drop aeration unit to provide

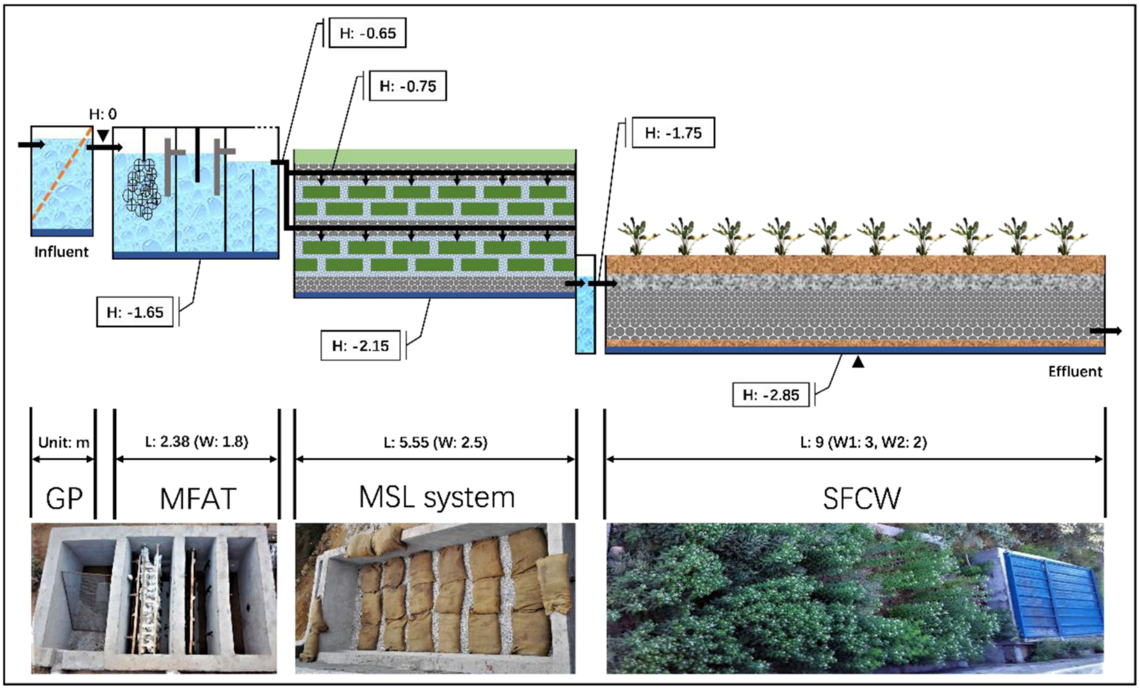

Fig. 5 The schematic configuration of on-site IGWTS application

the required DO concentration for the following MSL system. That is an effective design without additional power input for aeration. Furthermore, sludge applied as organic fertilizer could be used in courtyard garden or agricultural farmland as a green alternative to the commercial chemical fertilizer (Laitinen et al. 2017).

Secondary treatment in MSL system The high pollutant concentration still existed after the primary treatment in MFAT. The MSL system was featured with the high hydraulic load and removal efficiencies of organic matters and nutrients. Therefore, the MSL system was engineered as the core treatment unit in this integrated system. The three-dimensional structure diagram of the on-site MSL system in IGWTS is shown in Fig. 6. There were two wastewater distribution pipelines in the upper and middle of PLs, respectively. The soil, sand, sawdust (rice straw), charcoal, and iron powders (5:3:1:0.5:0.5 in dry weight) in SMBs were used and these materials were packed into jute bags. The pollutants can be removed in the MSL system through various physical, chemical, and microbiological mechanisms. The oxygen level in PLs and the edges of SMBs could be relatively high, and that would be favorable to aerobic activities. However, the inner part of SMBs tends to be with limited oxygen, which make it more anaerobic. In addition, a certain amount of nutrients can also be removed in MSL system. Both assimilation of phosphorus-accumulating bacteria and precipitation with the Fe hydroxides in MSL system could contribute to TP removal (Sato et al. 2011). Large-sized zeolites in PLs would be favorable for NH_3-N removal. Both nitrification and denitrification processes can occur in the same MSL system due to its unique structure. At the end of MSL system, effluent was discharged into a service reservoir for settling precipitation and water redistribution. In order to avoid the negative effect of bottom submersion shown in lab tests, the water outlet was put in the bottom of MSL system with surrounding gravels.

Tertiary treatment in SFCW After the treatment in MSL system, there was a significant decrease of pollutant level. The constructed wetland was used to further improve the quality of treated water. The surface flow constructed wetland was applied because it has less risk for clogging (Leverenz et al. 2009). SFCW consisted of clay (0.1 m high), coarse gravel (grain size 0.05 m, 0.2 m high), fine gravel (grain size 0.01–0.02 m, 0.5 m high), sand (grand size 0.002 m, 0.2 m high), and soil from the bottom up. In SFCW, contaminants could be removed through retention, biodegradation, and plant uptake in the rhizosphere while the wastewater passed through the layered bedding media. In addition, aquatic plant can play an important role in the constructed wetland. Bulrush (*Phragmites communis*) was used in the SFCW because it is one of the most ubiquitous aquatic plants in the study area, which is feature with fast adaptation and growth in wetlands. Its rhizosphere microbial membrane has high effectiveness in removing BOD_5, TN, and TP from wastewater (Bezbaruah and Zhang 2005). Moreover, some other functions of bulrush, such as absorbing heavy metals and toxins, providing oxygen to the submerged system through photosynthesis, and improving the pore structure and fertility of soil, have been reported (Mallison and Thompson 2010).

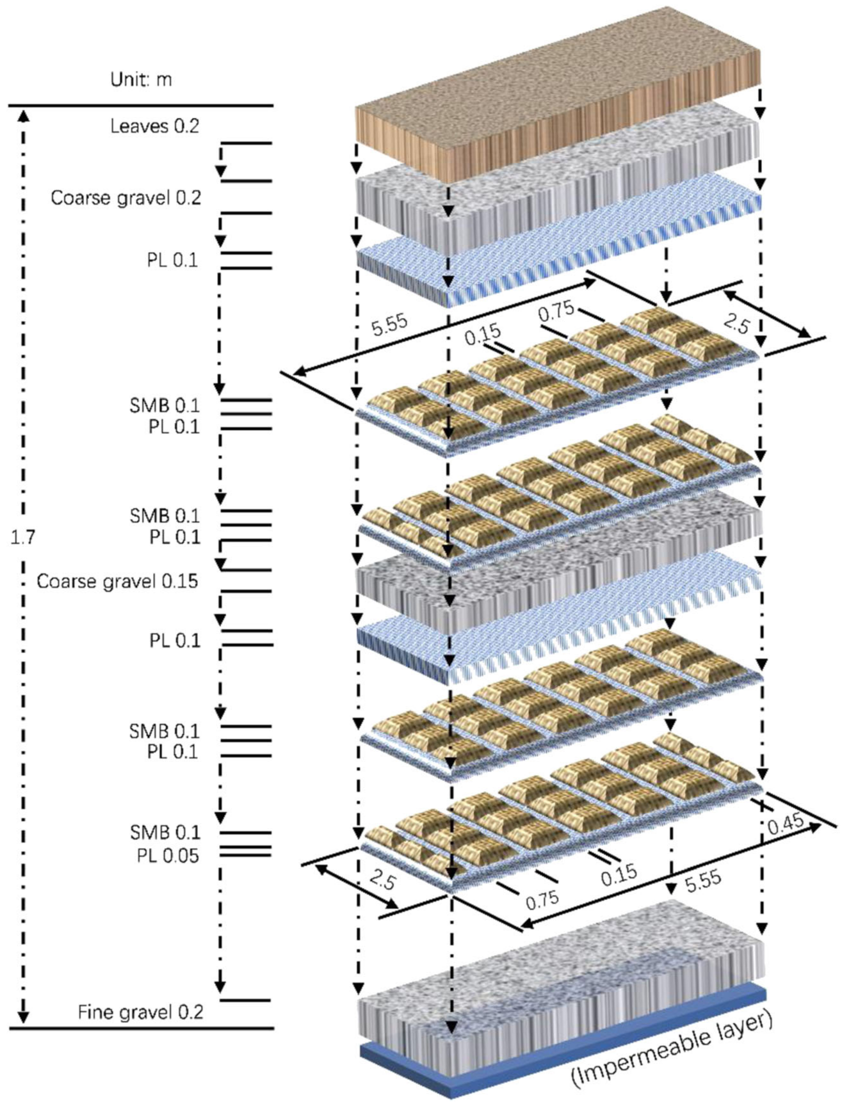

Fig. 6 The three-dimensional structure diagram of MSL system in IGWTS

Treatment performances of IGWTS modules

Contaminant removal performances varied in different modules of IGWTS. Fig. 7 shows the contaminant concentration in influent and effluent as well as the corresponding removal rate of each IGWTS module in stable operation. It can be seen the most efficient treatment was done in MSL system, the removal rates of COD, BOD_5, TP, NH_3-N, and TN were 92, 93, 92, 86, and 76%, respectively. The contributions of IGWTS modules to contaminant removal are also shown in Fig. 7. Obviously, MSL system provided the major contribution for treating domestic wastewater in IGWTS. The contributions of MSL system for removing COD, BOD_5, TP, NH_3-N, and TN were 77, 75, 87, 85, and 83%, respectively. Although SFCW showed better capacity to removal organic matters and nutrients, MFAT had more contribution to contaminant removal for helping to reduce the pollutant load in wastewater before entering MSL system. After the whole process of IGWTS, the effluent achieved a good quality with COD, BOD_5, TP, NH_3-N, and TN of 22.0, 8.0, 0.3, 4.0, and 11.0 mg/L, respectively. Such treated water met the high-level local requirement for discharging and could be further reused for landscaping or irrigation (Jin et al. 2014), making the wastewater to be no longer a “wastewater” but a “water resource”.

Water environment impact assessment of IGWTS

The calculated comprehensive trophic level index (CTLI) of final effluent was 59.2 mg/L, at a moderate level in the range of estimation scale from 0 to 100 mg/L (Huo et al. 2013). Although IGWTS showed a satisfied treatment performance, the FEP of final effluent impact on water environment still cannot be ignored. However, CTLI decreased to 49.6, 34.0, and 8.8 mg/L when reducing the concentrations of organic matters and nutrients to its 0.5, 0.1, and 0.01 times lower than the present levels, respectively. The chronic toxicity criteria of

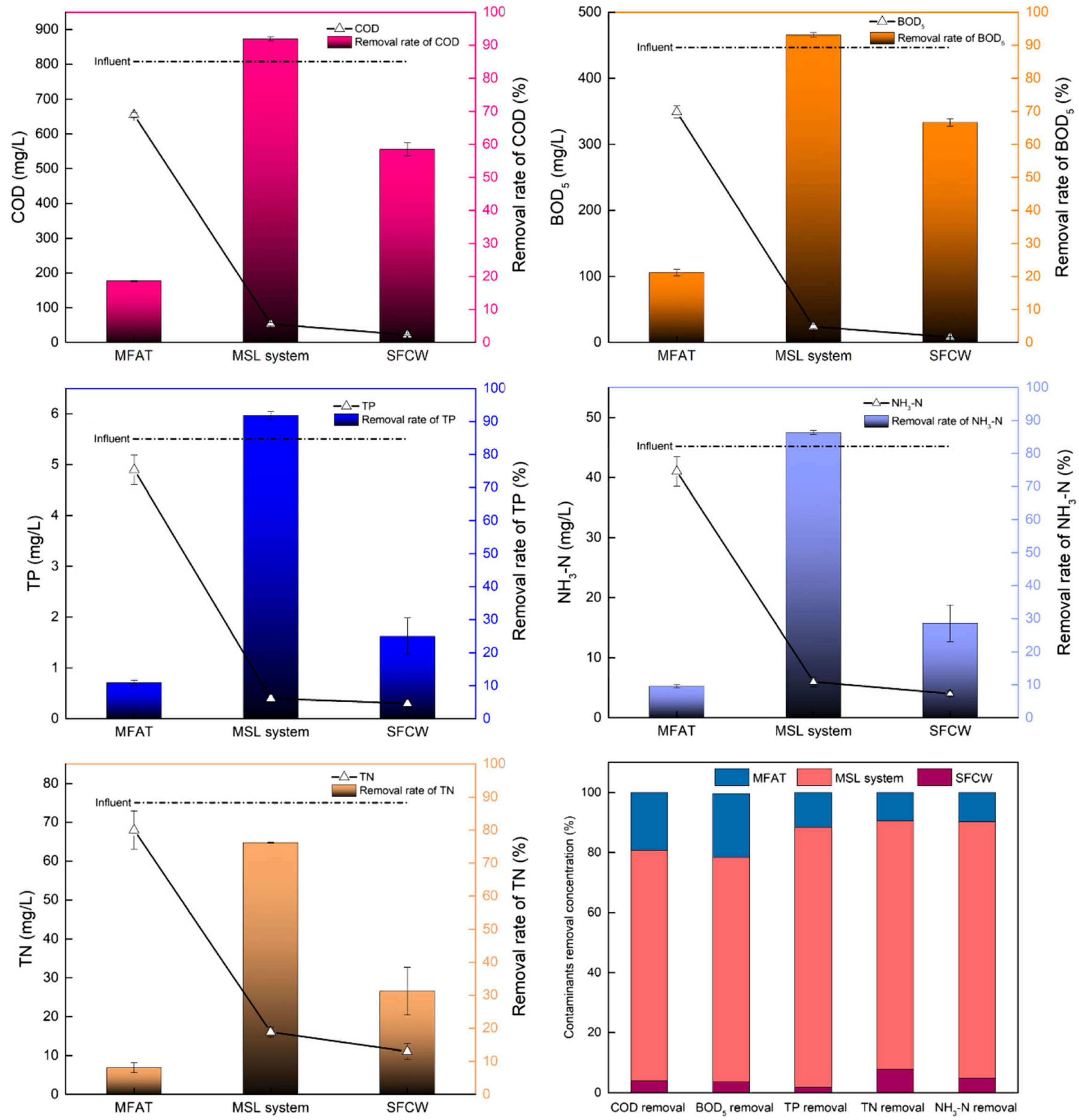

Fig. 7 The concentration variations of COD, BOD_5, TP, NH_3-N, and TN in effluent water along with their corresponding removal rates in each individual subsystem in stable operation, and the contributions of contaminant removal among three subsystems (MFAT, MSL system, and SFCW)

NO_3^- (CTC-NO_3^-) and acute toxicity criteria of NO_3^- (ATC-NO_3^-) to aquatic organisms were 5.2 and 88.0 mg/L. Based on the concentrations of NH_3-N and TN in final effluent, the maximum concentration of NO_3^- was approximately 7.0 mg/L. By comparison, there would be a certain extent of chronic toxicity of NO_3^- to aquatic ecosystem along with the long-term effluent discharging. However, rural domestic wastewater treated by IGWTS ensured a relatively secure NO_3^- concentration which was much lower than its ATC-NO_3^-. FAETP of final effluent to water environment could be significantly reduced to a level that was lower than CTC-NO_3^-. Thus, the final effluent from IGWTS could be reused for domestic, landscaping, and agricultural activities in rural areas rather than directly discharging to surface waters. Additionally, the FEP and FAETP of treated water could be further reduced through natural approaches such as bio-utilization, soil sorption, and water dilution (Ding et al. 2015).

EFA of IGWTS

In order to assess the performance of a wastewater treatment technology, the investment costs of construction and operation are taken into account (Mao et al. 2015). Table 1 shows the detailed inventory about material consumptions and costs of IGWTS within system boundary during a 10-year period. The cost of land required for IGWTS was not

Table 1 Inventory of cost accounting and life cycle GHG emissions for IGWTS within system boundary

Source	Unit	MFAT	MSL system	SFCW	IGWTS
Inputs					
Influent					
Water flow	m^3/day	5	5	5	5
COD	kg/m^3	0.8060	0.6550	0.0530	0.8060
BOD_5	kg/m^3	0.4430	0.3490	0.0240	0.4430
TP	kg/m^3	0.0055	0.0049	0.0004	0.0055
TN	kg/m^3	0.0740	0.0680	0.0160	0.0740
NH_3-N	kg/m^3	0.0449	0.0409	0.0060	0.0449
Construction					
Technician remuneration	USD	44.098	132.294	117.595	293.987
Field construction cost for labor	USD	146.994	367.485	283.987	798.466
Brick-concrete structure cost	USD	396.884	987.799	1270.028	2654.711
Geomembrane cost (quantity)	3.822 USD/m^2	191.10 (50)	229.32 (60)	248.43 (65)	668.85 (175)
Pensile carrier cost (quantity)	44.098 USD/m^3	52.9176 (1.2)	0	0	52.9176 (1.2)
Carriers bracket cost	USD	283.987	0	0	283.987
Gravels, zeolites, etc. cost (quantity)	27.9289 USD/m^3	0	837.867 (30)	726.1514 (26)	1564.0184 (56)
Plastic net cost (quantity)	2.2049 USD/m^2	44.098 (20)	176.392 (80)	220.49 (100)	440.98 (200)
Precast slab cost	USD	264.5892	0	0	264.5892
Louver cost (quantity)	5.8798 USD/m^2	17.6394 (3)	0	0	17.6394 (3)
Pipes and valves cost	USD	146.996	220.493	73.498	440.987
Safety responsibility billboards	36.7485 USD/m^2	73.497 (2)	0	0	73.497 (2)
Aquatic plant cost (quantity)	14.6994 USD/m^2	0	0	330.7365 (22.5)	330.7365 (22.5)
Electricity cost (quantity)	0.0882 USD/kWh	2.205 (25)	2.205 (25)	2.205 (25)	6.615 (75)
Total cost for construction	10^3 USD	1.6650	2.9539	3.2731	7.8920
Operation					
Medium-term repair cost for labor	10^3 USD	0.0882	0.1469	0.0735	0.3086
Maintenance cost for labor	10^3 USD	0.5879	0	0.4409	1.0306
Cost for operation	10^3 USD/year	0.0676	0.0147	0.0514	0.1337
Average operation cost for wastewater treatment	USD/m^3	0.0367	0.0007	0.0279	0.0653
Outputs					
Effluent					
COD (Total removal)	kg/m^3	0.6550 (0.1510)	0.0530 (0.6020)	0.0220 (0.0310)	0.0220 (0.7840)
BOD_5 (Total removal)	kg/m^3	0.3490 (0.0940)	0.0240 (0.3250)	0.0080 (0.0160)	0.0080 (0.4350)
TP (Total removal)	kg/m^3	0.0049 (0.0006)	0.0004 (0.0045)	0.0002 (0.0001)	0.0002 (0.0052)
TN (Total removal)	kg/m^3	0.0680 (0.0006)	0.0160 (0.0520)	0.0110 (0.0050)	0.0110 (0.0576)
NH_3-N (Total removal)	kg/m^3	0.0409 (0.0040)	0.0060 (0.0350)	0.0040 (0.0020)	0.0040 (0.0410)
Operation					
CH_4 from sludge	kg CO_2-eq/m^3	0.3019	0	0	0.3019
CH_4 from wastewater treatment	kg CO_2-eq/m^3	0.4529	0.0377	0.0192	0.5098
N_2O from wastewater treatment	kg CO_2-eq/m^3	0.0141	0.0049	0.0185	0.0374
Total GHG emissions	kg CO_2-eq/m^3	0.7689	0.0426	0.0377	0.8491

considered because the new system was constructed using the currently available space with a simplified tank. The inventory management of GP was integrated into MAFT. Besides, safety responsibility expenditure was considered as an important term which is obligatory cost, though this is a small project in rural area. The building materials, aquatic plants, and labor cost accounted for a large proportion (99.9%) of total cost for construction while electricity consumption only occupied 0.1%. The cost proportions of constructing MSL system and SFCW were 37% and 42%, respectively, according to their material requirements. During the period of system operation, the medium-term repair of IGWTS would be carried out in the 5th year, and the routine maintenance including water quality monitoring, wearing part replacement, sludge disposal, aquatic plant cultivation, and performance evaluation would be carried out once half a year. For rural community, the average cost for operation is only 133.7 USD/year. In particular, the average operation cost for treating 1 m^3 domestic wastewater is only 0.0653 USD. The average operation cost of MSL system for wastewater treatment was the lowest (0.0007 USD/m^3), while it showed the best performance for decontamination among these IGWTS modules. The economic leverage as sound management strategy could efficiently resolve the dilemma of water pollution in developing countries. The results of economic feasibility analysis (EFA) would be a sufficient support for promoting the future application of MSL-based IGWTS in more rural areas.

Life cycle GHG emission assessment of IGWTS

GHG emission assessment can help evaluate the sustainability of wastewater treatment technology. Based on the computational method from IPCC (Bastianoni et al. 2014; Munoz and Schmidt 2016), the CH_4 (CO_2-eq) and N_2O (CO_2-eq) emissions from both sludge handing and wastewater treatment process of IGWTS were summarized in Table 1. CH_4 is the major GHG emitted from sludge disposal and its CO_2 equivalent quantity was about 0.3019 kg CO_2-eq/m^3. The emissions of CH_4 and N_2O from wastewater treatment were 0.5098 and 0.0374 kg CO_2-eq/m^3, respectively. Compared to N_2O, almost 96% of GHG emissions about CH_4 was contributed by IGWTS. Among three subsystems as shown in Fig. 8, GHG emissions from MFAT had the largest contribution (91%), while both MSL and SFCW showed less GHG emissions (5 and 4%, respectively). In MFAT, CH_4 generation was mainly attributed to the anaerobic

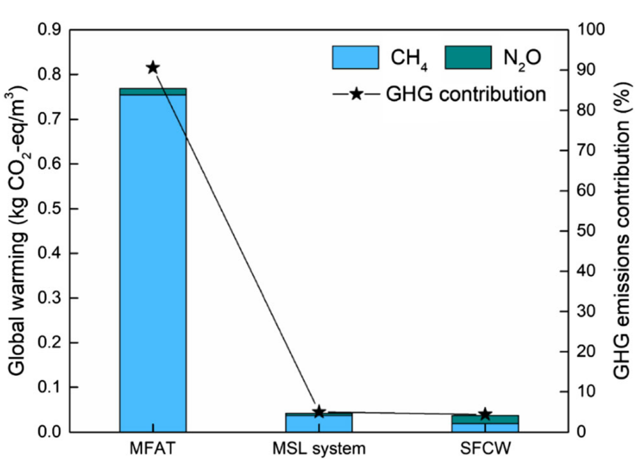

Fig. 8 The global warming impact of each subsystem in IGWTS

biodegradation reaction in which small molecular organic acid could be converted to CH_4 through methanogens.

Although the largest part of organic matter was removed by MSL system, the GHG emissions from MSL system was limited due to the unique brick-pattern structure of soil-based system, which could achieve efficient wastewater distribution and air diffusion as well as contact between each other. In this study, the organic matter and GHG emission ratios (COD/CH_4) in MFAT and IGWTS were 5.1 and 1.1, respectively, which showed a superior performance in terms of the mitigation of GHG emission using this developed green decentralized wastewater treatment system. However, the COD/CH_4 ratio for municipal wastewater treatment plant was more than 7 due to a large amount of intensive GHG emissions from additional investment of capital and equipment (Shahabadi et al. 2009; Yerushalmi et al. 2013). In present study, IGWTS had 4.245 kg CO_2-eq/day of GHG emissions, which meant that about 1.952 kg CO_2-eq of GHG emissions were accounted for removing 1 kg BOD_5. In comparison, the relative GHG emissions (per 1 kg BOD_5 removal) of IGWTS was significantly lower than the wastewater treatment plant with 7.3 kg CO_2-eq of relative GHG emissions (per 1 kg BOD_5 removal) (Pan et al. 2011), and the traditional vertical subsurface flow constructed wetland with 5.3 kg CO_2-eq of relative GHG emissions (per 1 kg BOD_5 removal) (Zhang et al. 2019). The GHG emissions from the wastewater treatment activities are inevitable. However, the potential GHG emissions could be controlled through appropriate management of sludge disposal. In MFAT, sludge handing had the considerable CH_4 contributions to total CH_4 emission (37%) and total GHG emissions (36%), respectively, which should be paid special attention. It is recommended to utilize the captured CH_4 as secondary energy for heat or electricity generation. This is the most sustainable approach to mitigate the atmospheric warming impact of CH_4 production from wastewater treatment system, even it will take high costs for necessary technology and equipment. Wastewater was treated completely in IGWTS through ecological mechanisms without any energy consumption along with GHG emissions. Thus, IGWTS is a sound approach for both domestic wastewater treatment and GHG emission reduction in rural areas.

Conclusion

In this study, the innovative IGWTS for domestic wastewater treatment in rural areas was developed. As the core module of IGWTS, MSL system showed good performances for removing organic matters and nutrients in lab-scale experiments. Aeration was found to be the dominant positive factor for contaminant removal in factorial analysis, while bottom submersion had the most negative effect. Based on the critical operational factors obtained from lab-scale tests, the full-scale IGWTS consisting of MFAT, MSL, and SFCW was designed, constructed, and operated successfully in the field application. As an integrated system, the modules within IGWTS were complementary to each other, and IGWTS showed good performances in the removal of COD, BOD_5, TP, NH_3-N, and TN. The quality of treated water met the local stringent requirement for discharging. The feasibility of IGWTS was also quantitatively evaluated from the perspectives of material and energy consumption, economic costs, water environment impact, and life cycle GHG emissions.

IGWTS was proved to be a sound approach to mitigate global warming impact in terms of its lower GHG emissions compared with centralized wastewater treatment method. It can be featured as an eco-friendly and cost-effective technology to improve rural water environment. IGWTS also presented many other advantages such as low land-space requirement, good landscape appearance, less material consumption and chemical usage, easy operation and maintenance, extremely low energy consumption, long service lifespan, odor and color free, and operation without noise. Thus, IGWTS is a sustainable solution to deal with the contradictions among the improvement of rural community, economy, and eco-environment. Further study will be needed to further explore the performance of IGWTS under complicated environmental conditions.

Acknowledgments The authors are grateful to the editor and the anonymous reviewers for their insightful comments and suggestions.

Funding information This research was supported by the National Key Research and Development Plan (2016YFC0502800, 2016YFA0601502), the Natural Sciences Foundation (51520105013, 51679087), the 111 Program (B14008), the Natural Science and Engineering Research Council of Canada, and the United Nations Development Programme.

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