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Research Article

Full-scale application and performance of a new multi-self-reflow decentralized Wastewater treatment device: Impact of hydraulic and pollutant loads

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ABSTRACT

Decentralized treatment of wastewater in rural areas usually has several challenges, which include large fluctuations in pollutant concentration and water quantity, complicated operation and maintenance of conventional biochemical treatment equipment, resulting in poor stability and a low compliance rate of the wastewater treatment process. In order to solve the above problems, a new integration reactor is designed, which uses gravity and aeration tail gas self-reflux technology to realize the reflux of sludge and the nitrification liquid, respectively. The feasibility and operation characteristics of its application for decentralized wastewater treatment in rural areas are explored. The results demonstrated that, under constant influent, the device showed strong tolerance to the shock of pollutant load. The chemical oxygen demand, NH_4^+-N, total nitrogen and total phosphorus fluctuated in the ranges of 95–715 mg/L, 7.6–38.5 mg/L, 9.32–40.3 mg/L and 0.84–4.9 mg/L, respectively. The corresponding effluent compliance rates were 82.1%, 92.8%, 96.4% and 96.3%, respectively. When the wastewater discharge was non-constant and the maximum single-day Q_{max}/Q_{min} reached 5, all indicators of the effluent met the relevant discharge standard. The integrated device also demonstrated high phosphorus enrichment levels in its anaerobic zone; the concentration of phosphorus reached a maximum of 26.9 mg/L, which created a good environment for phosphorus removal. The microbial community analysis showed that sludge digestion, denitrification, and phosphorus-accumulating bacteria all played an important role in pollutant treatment.

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Introduction

Decentralized wastewater in villages, tourist spots, and other areas is an important part of the social water cycle, and will cause severe pollution if not managed properly (Estévez et al., 2022; Massoud et al., 2009; Torre et al., 2021). Due to the difference in the geographical environment, it is difficult to collect and treat decentralized sewage in a centralized way. Hence, such wastewaters need to be treated *in situ* according to local conditions (Geetha Varma et al., 2022; Huang et al., 2021; Libralato et al., 2012). In developed countries, the population in rural areas is relatively sparse. In most cases, compliant discharge of wastewater can be achieved via simple collection and *in situ* treatment. However, in developing countries with a high population density, the quantity of wastewater often exceeds the capacity of the surrounding environment (Massoud et al., 2009; Yang et al., 2021). Therefore, the construction of small-scale decentralized sewage treatment devices is of great significance for decentralized wastewater treatment.

The components of decentralized wastewater are simple, with the main pollutants being organic matter, nitrogen, and phosphorus. Biochemical processing has always been the preferred water treatment method because of its cost- effectiveness. Generally, the development of the various equipment is based on the principles of nitrification/denitrification for nitrogen removal and biochemical- assisted physicochemical processes for phosphorus removal, such as a sequence batch reactor (SBR), an anaerobic-anoxic-aerobic (A^2/O) process, multistage biological filters, and biological turntables (Han et al., 2019; Zha et al., 2018). Theoretically, these effective and experienced equipment for the treatment of urban sewage should have the same good treatment effect when applied to decentralized sewage treatment (Fang et al., 2016; Liu et al., 2020). However, the operating rate and effluent quality compliance of the currently available decentralized wastewater treatment equipment were found to be low, and many sewage treatment facilities cannot operate normally (Yang et al., 2021). This phenomenon primarily due to the unique characteristics of decentralized wastewater, that are primarily reflected in the following aspects: (1) The quantity of rural decentralized sewage is small, and the fluctuation coefficient of the water quality and quantity is large. For example, residents have three meals a day and diurnal cycles, resulting in fluctuations in water quality and quantity several times a day (Guo et al., 2014). Therefore, the distributed sewage treatment facilities must have high resistance to instantaneous water volume and pollutant load shock. (2) Although the wastewater treatment equipment are typically small, they are equipped with all the components required for the complete treatment of wastewater, so the systems require professional management (Song et al., 2020). However, rural funds are sparse, making it difficult to pay a full set of professionals to operate and manage the equipment, that would include electromechanical maintenance personnel, technical managers, and water quality monitors (Guo et al., 2014). Therefore, decentralized wastewater treatment equipment should be highly integrated in the technology and reduce the need for electromechanical equipment as much as possible. In summary, how to build an integrated treatment equipment that meets the characteristics of decentralized sewage, enhances the resistance to shock loading, and reduces the maintenance frequency is very important for the efficient operation of decentralized wastewater treatment.

To solve the above problems, through the design of a vertical space structure, this study develops a set of integrated equipment with anaerobic, aerobic and sedimentation functions, that rely on gravity sedimentation to realize the self-reflux of sludge and collect the tail gas in the aerobic area as power to realize the self- reflux of nitrification liquid. The only electromechanical components of this integrated device are a blower and an inlet pump. This system thus simplifies the equipment requirements of the nitrification liquid reflux pump and sludge reflux pump and realizes a high integration of wastewater treatment technologies. The purpose of this study is to explore the pollutant transformation characteristics during the operation of the equipment, determine the impact of long-term or short-term hydraulic load and pollutant load fluctuations on the treatment efficiency of the reactor, and investigate the structure of the related microbial community.

1. Material and methods

1.1. Technology and operational method

The wastewater treatment system consists of two parts: an integrated device with self-reflux and a filter tank (Fig. 1). Both parts are made of polyethylene plates. The integrated device is cylindrical in shape with a diameter of 2.7 m, height of 2.8 m, and an effective volume of 14 m^3. The volumes of the internal aerobic, anaerobic, and precipitation zones are 6.6 m^3, 4.8 m^3, and 2.6 m^3, respectively. The filter tank is cylindrical in shape with a diameter of 0.5 m and height of 1.2 m, with an effective volume of 0.21 m^3. During the start-up stage, the system is inoculated with activated sludge from a municipal wastewater treatment plant; the concentration of the sludge is 3560 mg/L. The raw wastewater first enters the anaerobic zone of the integrated device, where the main reactions include hydrolysis and acidification of large organic particles, organic nitrogen ammonization, denitrification of NO_3^--N, anaerobic phosphorus release of the phosphorus-accumulating bacteria (PAO); and the storage and digestion reactions of sludge. Then, the anaerobic effluent enters the aerobic zone, where the main reaction is the removal of residual organic matter, the nitrification of ammonia nitrogen and the uptake of phosphorus by PAO. The dissolved oxygen (DO) in the aerobic zone is higher than 1 mg/L, which is controlled by the air intake of the blower. Part of the wastewater in the aerobic zone is returned to the anaerobic zone by the gas-lift reflux system, and the other wastewater is put into the precipitation tank to realize sludge-water separation. The effluent from the precipitation tank enters the filter tank and the sludge flows back along the diversion pipe to the anaerobic zone. The FeS_2 in the filter tank thoroughly treats the phosphorus in the effluent of the integrated device through chemical reactions. At the same time, to tackle the problem of high levels of suspended solids (SS) in the effluent of the integrated device due to load fluc-

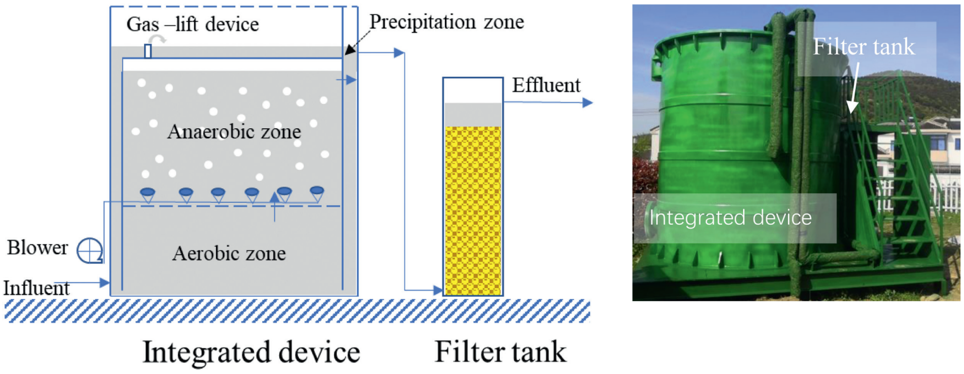

Fig. 1 – Process flow diagram of decentralized wastewater treatment.

Table 1 – Water quality characteristics

Water quality index	Raw water concentration	Emission limits
COD (mg/L)	241.5±129.7	<50
NH_4^+-N (mg/L)	16.9±6.6	<5
TN (mg/L)	20.6±6.5	<20
TP (mg/L)	1.6±0.8	<1
SS (mg/L)	50±32.1	<20
Temperature (°C)	24.8±2.5	/

tuations, the filter tank is also made to physically intercept it. The filter tank is backwashed every night and the backwashed wastewater is returned to the adjustment tank. During the operation of the system, polyferric chloride (5 kg each time) is added to the anaerobic zone periodically (every 20 days) to precipitate the enriched phosphorus and flocculate the sludge, followed by sludge discharge in the anaerobic zone to remove the phosphorus and adjust the sludge age.

1.2. *Wastewater characteristics*

The wastewater used was collected from the domestic sewage wastewater of a village located on Xishan Island in Jinting Town, Wuzhong District, Suzhou City, China. Since this island is a scenic spot, the water quality and quantity not only fluctuate with the resident living habits but also with seasonal tourism. Additionally, since the Tai Lake is a source of domestic water for many cities, the wastewater discharge standard is high. Special discharge standards of Jiangsu Province are strictly implemented. The water quality and effluent indicators are presented in Table 1.

1.3. *Analytical method*

The chemical oxygen demand (COD), NH_4^+-N, total nitrogen (TN), total phosphorus (TP), and SS of the wastewater and the effluent from the device were measured using wastewater analytical methods (APHA, 2005). The COD was measured using the potassium dichromate method. NH_4^+-N and TN were measured using Nessler reagent spectrophotometry and ultraviolet spectrophotometry, respectively. TP was measured using ammonium molybdate spectrophotometry. The concentration of the sludge was measured using the HACH TSS portable (USA) analyzer. DO was measured using the HACH (HQ40d, USA) multiple parameter water quality analyzer.

1.4. *Experimental method*

This study mainly discusses the influence of the change in the hydraulic and pollutant loads on the treatment efficiency of the integrated device when it is used to treat decentralized wastewater. However, the related filter tank efficiency is not discussed in detail. During the initial start-up stage of the device, the hydraulic retention time (HRT) was set to be 0.97 day to understand its impact on pollutant removal. Subsequently, the hydraulic load of the integrated device was increased by gradually shortening the HRT in order to understand the influence of pollutants and the hydraulic load on pollutant removal. After 38 days, 69 days and 117 days of reactor operation, HRT will be reduced to 0.83 day, 0.73 day and 0.69 day respectively. In order to make the reactor adapt to the living habits of village residents and the pattern of wastewater discharge, one day was used as the test cycle, and the influence of the unsteady inflow on the removal of pollutants in the system was determined. In addition, under the condition of a constant influent, different air intakes and a run of 27days in each stage were utilized to explore their influence on the reflux characteristics and system treatment efficiency.

1.5. *Microbial community analysis*

In order to further analyze the pollutant transformation characteristics in each area of the integrated device, the inoculated sludge and the sludge in the anaerobic and aerobic areas of the integrated device after 180 days operation were taken out for microbial community structure analysis. The microbial communities in sludge samples were analyzed by 16S rRNA sequencing on the Illumina MiSeq platform. The PCR primers 357wF (CCTACGGGGNGGCWGCAG) and 785R (GACTACHVGGGTATCTAATCC) were used. The operating procedures and parameters are based on Wang et al. (2022).

1.6. *Calculation method*

The quality and quantity of decentralized sewage are constantly changing. The performance evaluation of decentralized sewage treatment devices cannot be limited to the removal of pollutants and whether the effluent concentration meets the standard. Therefore, this study adopts pollutant load and compliance rate to evaluate the comprehensive performance of the decentralized sewage device (Yang et al., 2021). The compliance of various pollutants is based on the local wastewater discharge standards, as shown in Table 1. The main calculations are publicized as follows:

$$\text{COD load rate} = C_{\text{CODi}}/\text{HRT} \tag{1}$$

$$\text{TNload rate} = C_{\text{TNi}}/\text{HRT} \tag{2}$$

$$\text{Compliance rate} = 100 * n_i/\text{Tn}_i \tag{3}$$

Where C_{CODi} (g/L) is the influent concentration of COD; HRT (day) refers to the hydraulic retention time of the integrated device; C_{TNi} (g/L) is the influent concentration of TN; n_i refers to the number of times that pollutant *i* meets the emission standard; Tn_i is the total number of times that pollutant *i* is detected.

2. Results and discussion

2.1. *Start-up of the integrated device*

COD is one of the main pollutants in municipal wastewater, accounting for the largest proportion (Pang et al., 2017). In the process of wastewater treatment, except denitrification and phosphorus removal in anaerobic environment consume part of COD, the rest of COD should be removed by sufficient DO oxidation in aerobic zone (Pelaz et al., 2018; Zhang et al., 2021). The quality of decentralized sewage fluctuates relatively significantly, and the fluctuation of the COD load easily leads to insufficient DO in the system, resulting in an increase in the effluent concentration of COD, NH_4^+-N and TP (Zhang et al., 2019). Therefore, the complete removal of COD is critical to the efficient removal of other pollutants. The HRT was set to be 0.97 day during the initial stage (0–37 days). The influent COD concentration was in the range of 110–634 mg/L, and the COD load rate was within 0.13–0.65 kg/(m^3·day). When the influent COD load rate was above 0.5 kg/(m^3·day), the effluent COD concentration was sometimes above 50 mg/L, and in other states, the effluent COD concentration is always lower than 50 mg/L (Fig. 2**a**). During this period, the concentration of DO in the system was greater than 1 mg/L (Appendix A Fig. S1). Hence, the DO provided by the system was sufficient. This indicates that at the initial stage of start-up, the number of microorganisms in the system was relatively small and could not meet the environmental needs, rather than the insufficient dissolved oxygen, which leads to the low ability of the system to resist organic load shock.

Table 2 – change of pollutant compliance rate during startup of integrated device

Time (day)	COD (%)	NH_4^+-N (%)	TN (%)	TP (%)
0-37	85.2	92.6	100	92.6
38-85	97.5	97.5	97.5	97.6
86-116	82.1	92.8	96.4	96.3
117-180	68.8	83.3	91.7	91.7

To further increase the system microorganism concentration, the HRT was shortened to 0.83 day between days 38–85 of the running. During this stage, the effluent COD load rate was within 0.12–0.86 kg/(m^3·day). However, the effluent COD did not significantly increase with the increase in the system load in most of the time. The COD compliance rate was 97.6% (Table 2). Only when the COD concentration of influent reaches 715 mg/L at 56 days, the COD of effluent rises to 77.6 mg/L. The HRT was shortened to 0.73 day between days 86–116. During this state, the influent concentration of COD was in the range of 103–480 mg/L and the COD load rate was within 0.14–0.66 kg/(m^3·day). When the effluent COD load rate was above 0.47 kg/(m^3·day), the effluent COD concentration was above 50 mg/L, with the highest value being 86 mg/L. The COD compliance rate was 82.1% during this stage. During 118–180 days, the HRT was shortened to 0.69 day. During peak tourist season, the large number of tourists on weekends led to periodical change in the raw water quality. During this stage, the influent COD concentration was in the range of 102–577 mg/L, and the COD load rate was within 0.15–0.84 kg/(m^3·day). During this stage, when the inflow COD load rate was above 0.4 kg/(m^3·day), the effluent COD concentration was above 50 mg/L, with the highest value being 67.8 mg/L. The COD compliance rate decreased to 68.8%. Overall, as the HRT was shortened gradually, the ability of the device to withstand COD load rate fluctuations decreased gradually.

The removal of nitrogen in wastewater requires enough DO to oxidize NH_4^+-N into NO_2^--N or NO_3^--N, and sufficient reflux to return them to the front end for denitrification with influent COD. During the initial stage (0–37 days), the influent NH_4^+-N and TN was within 10.75–30.2 mg/L and 12.82–31.7 mg/L, respectively (Fig. 2**b, c**). The TN load rate was within 13.2–32.6 g/(m^3·day). The effluent NH_4^+-N concentration was below 5 mg/L, and the effluent TN concentration was below 13.54 mg/L. The phenomenon indicated that the system had a strong nitrification and denitrification capacity to achieve nitrogen treatment. When the HRT was shortened to 0.83 day, the concentrations of effluent NH_4^+-N and TN were compliant (up to 5.78 and 23.06 mg/L, respectively) only when the effluent COD concentration reached 717 mg/L. It was speculated that the concentration of NH_4^+-N increased as a result of incomplete conversion of the system COD. Qiu et al. (2009) also found that the effluent concentration of NH_4^+-N would increase when the COD in the system fluctuated greatly in a two-stage membrane process to treat the decentralized wastewater. When the HRT was shortened to 0.73 day, the influent concentrations of the NH_4^+-N and TN were in the range of

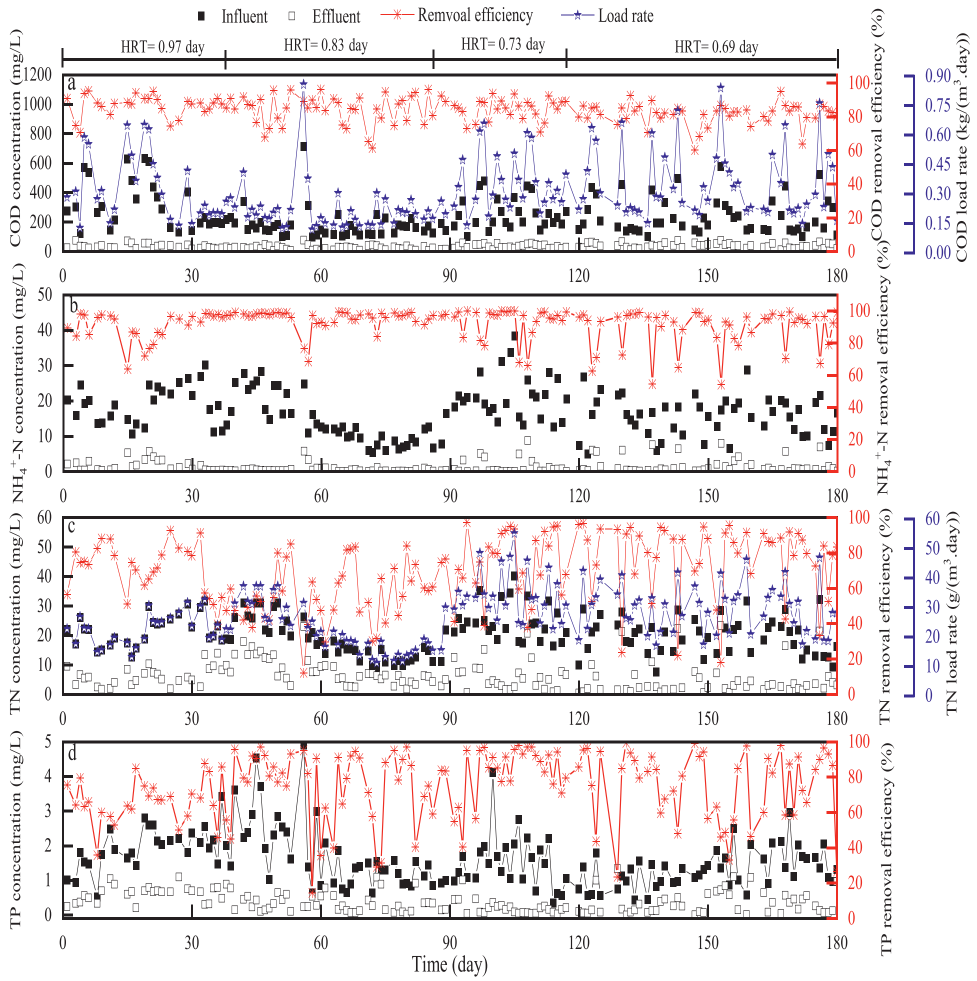

Fig. 2 – The influence of pollutants and change in HRT on the start-up stage of the integrated device.

6.78–38.4 mg/L and 11.18–40.23 mg/L, respectively. The TN load rate was within 15.33–51.8 g/(m^3·day). The compliance rates of effluent NH_4^+-N and TN were 92.8% and 96.4%, respectively, and it only occasionally exceeded the discharge standard. The compliance rates did not show a correlation with the system nitrogen load rate but showed a significant correlation with the fluctuation of system COD load. When the HRT was shortened to 0.69 day, the concentrations of inflow NH_4^+-N and TN were in the range of 6.52–26.9 mg/L and 11.7–31.7 mg/L, respectively, and their corresponding compliance rates dropped to 83.3% and 91.7%, respectively.

Because the precipitation zone is in the upper portion and the anaerobic zone is at the bottom, the device has a high retention capacity for activated sludge, and operates in an environment with a high sludge concentration. A large amount of sludge could be anaerobically digested in the anaerobic zone, which maintained the low DO environment in the anaerobic zone. Meanwhile, when influent organic matter is scarce, the release of organic matter in the sludge provided a sufficient carbon source for PAO, which benefitted the absorption of phosphorus in an aerobic environment (Li et al., 2016). Yang et al. (2022) used a biofilm as the carrier to achieve phosphorus enrichment from 3 to 220 mg/L via the anaerobic/aerobic reciprocating cycle. In this study, the suspended sludge was used as the carrier to enhance the phosphate concentration above 26.9 mg/L via the alternating anaerobic/ aerobic cycle (Appendix A Fig. S2). This provides a good environmental condition for phosphorus removal by adding a phosphorus removal agent. Therefore, through the regular addition of phosphorus-removing agents and sludge discharge, the effluent phosphorus concentration could be maintained below 1 mg/L (Fig. 2d); the compliance rate was always above 90% when the inflow phosphorus concentration was in the range of 0.84–4.9 mg/L. Since the system was always maintained at a high sludge concentration, sludge overflow was observed on the sedimentation zone when the HRT was shortened to 0.69 day. The observation indicated that the optimal HRT was 0.73 day when treating raw water with such a level of fluctuation. Overall, the maximum water treatment capacity of the integrated device was found to be 19.2 m^3/day.

2.2. *Influence of airlift and reflux on the treatment efficiency of the integrated reactor*

In the integrated device, the reflux of nitrification liquid completely depends on the air-lift device, and the reflux volume is closely related to the intake air volume. When the intake air increases gradually from 1 to 10 m^3/hr, the reflux volume also

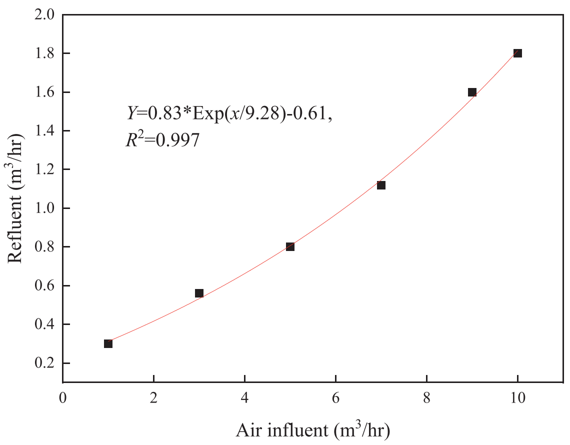

Fig. 3 – The influence of gas inflow volume on reflux volume.

increases gradually and reaches its maximum at 1.8 m^3/hr (Fig. 3). It was found that there was linear relationship between the gas intake and the amount of reflux nitrification liquid: $Y=0.83^{*}EXP(X/9.28)-0.61$, $R^2=0.997$. The impact of HRT on the device indicated that the maximum water volume that the system withstands was 19.2 m^3/day. Therefore, when the system nitrification liquid reflux ratio was above 2.25, it can satisfy the needs for wastewater treatment.

The amount of intake air not only affects the treatment effects of COD and NH_4^+-N, but also affects the stability of TN and TP removal in the system. To further understand the influence of air intake volume on pollutant removal, the HRT was set constant at 0.73 day and the air intake was increased gradually from 4 to 8 m^3/hr. The nitrification liquid reflux ratio was increased gradually from 0.85 to 1.8. The effluent water quality at each stage is shown in Fig. 4. Even when the air intake increased gradually, the COD and NH_4^+-N removal rates remained constant, and the effluent quality reached discharge standards without any significant change (Fig. 4**a, b**). The TN removal increased significantly with the increase in the air intake. The average increase in the removal from 44.61%±15.38% to 79.12%±13.38% (Fig. 4**c**). This indicates that an increase in the air intake produces more NO_3^--N reflux into the anaerobic zone for denitrification, and strengthens the removal of TN from the wastewater. However, the change in the phosphorus removal indicated that when the air intake was above 8 m^3/hr, even though the effluent phosphorus concentration met the standard, the phosphorus removal efficiency was low (Fig. 4**d**). It was speculated that the excessive increase in air intake increased the DO level in the nitrification liquid. Meanwhile, the increased reflux volume caused the PAO in the anaerobic zone to be poisoned by oxygen such that their phosphorus-releasing ability decreased, which led to the decreased phosphorus-absorbing capacity in the aerobic zone (Izadi et al., 2021; Yu et al., 2021). Therefore, the air intake should be below 8 m^3/hr when treating such a wastewater type.

Decentralized wastewater treatment devices exhibiting low energy consumption have gradually started attracting the attention of researchers over the past few years. Examples include gravity flow membrane reactors and multistage rotary biological contactors (Cheng et al., 2022; Lee et al., 2021). Thus, intelligent control function with low energy and low-cost features also became a focus of integrated decentralized wastewater treatment process (Brdys, 2010; O'Donovan et al., 2015). However, since the quality of decentralized wastewater varies greatly, precise control under a constant DO concentration requires not only sensitive DO monitoring equipment to feed data back to the system, but also a programmable logic controller (PLC) control system to adjust the air inlet volume of the blower in time (Zubowicz and Brdys, 2010). However, the frequent switch of a blower at different frequencies will accelerate equipment damage (Yang et al., 2021). Therefore, it is difficult to widely apply precise control in decentralized wastewater treatment process. The decentralized wastewater treatment scale is small, and if there exists a relatively constant air intake, the energy waste is relatively small. This will be more conducive to the system for the stable control of effluent COD and NH_4^+-N. However, achieving efficient, low energy consumption removal of TN from wastewater still remains a challenge (Oakley et al., 2010). Li et al. (2017) used the tail gas in the aerobic zone as the power during the PN-Anammox process, and they successfully achieved effluent reflux with a reflux ratio of over 8. To make the system operate with low energy consumption, this device also collects the aeration tail gas from the aerobic zone as power, and fully utilizes the energy to achieve nitrification liquid reflux.

2.3. *Influence of instantaneous flow change on the treatment efficiency of the integrated device*

The discharge of wastewater is the highest during the mornings and evenings and lowest at night due to resident living habits. The discharge also shows instantaneous increase and decrease characteristics. Therefore, the regulating tank needs to be designed in such a way that it withstands the water volume during the peak period, which will undoubtedly lead to an increase in the infrastructure cost. In this study, two modes (A and B) were used to understand the influence of instantaneous flow change on the integrated wastewater treatment device. This study also explored the tolerance of the wastewater treatment device to the impact of water quality and quantity under the two modes.

The influent of mode A was 14.2 m^3/day, with an average flow rate of 591.6 L/hr, a gas water ratio of 5, a minimum night wastewater flow rate of 300 mL/hr, a maximum wastewater flow rate of 900 mL/hr during mornings and evenings, and a Q_{max}/Q_{min} of 3 (Fig. 5**a**). The concentrations of the inflow COD, NH_4^+-N, TN, and TP were maintained in the range of 72–257 mg/L, 7.18–14.5 mg/L, 14–30 mg/L, and 0.66–2.12 mg/L, respectively. After 27 days of operation, the average effluent COD, NH_4^+-N, TN, and TP were found to be below 43 mg/L, 3.45 mg/L, 8.58 mg/L, and 0.34 mg/L, respectively (Fig. 5**b, c**). All indicators were within the corresponding wastewater treatment standards.

The influent of mode B was 14.2 m^3/day, with an average flow rate of 591.6 L/hr, a gas water ratio of 5, a minimum night wastewater flow rate of 200 mL/hr, maximum wastewater flow rate of 1000 mL/hr during mornings and evenings, and a Q_{max}/Q_{min} of 5 (Fig. 5**d**). The concentrations of the in-

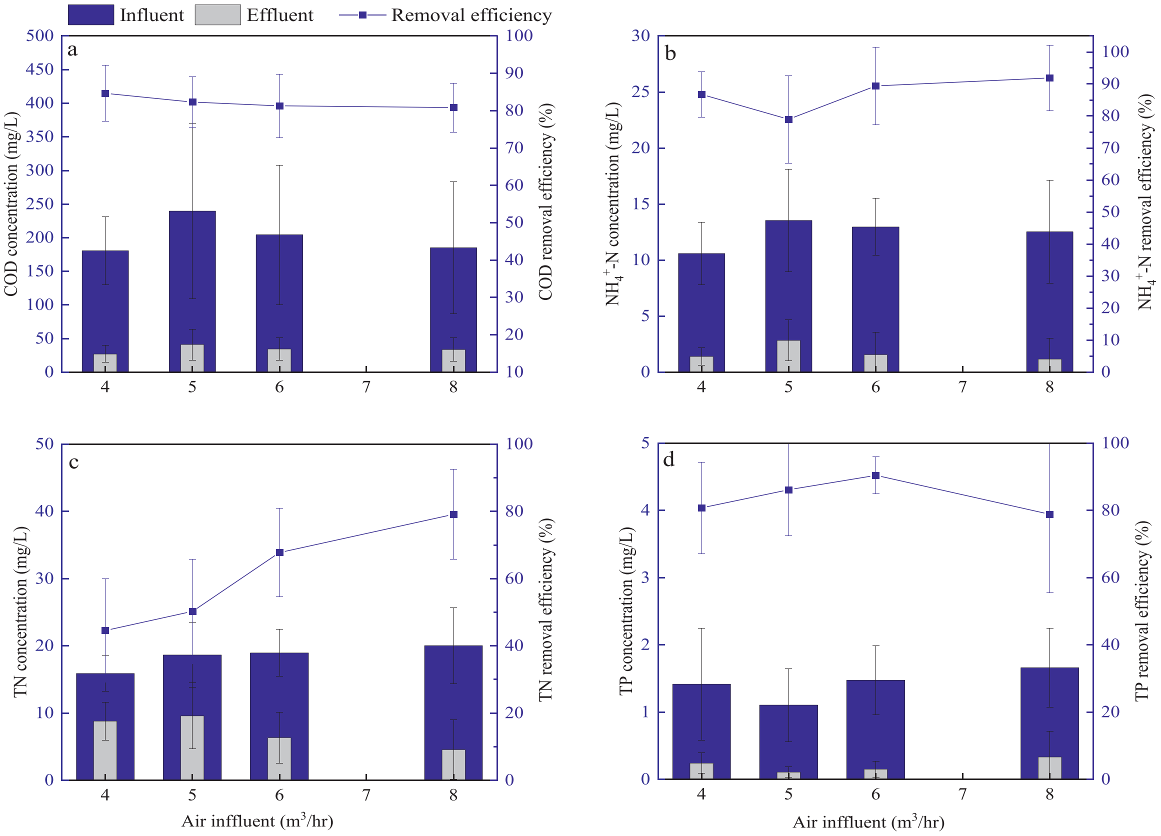

Fig. 4 – The influence of gas inflow volume on the initiating process of the integrated device.

flow COD, NH_4^+-N, TN, and TP were maintained in the range of 133–332 mg/L, 8.05–17.79 mg/L, 13.4–29.7 mg/L, and 0.59–1.99 mg/L, respectively. After 30 days of operation, the average effluent COD, NH_4^+-N, TN, and TP were found to be below 47.7 mg/L, 2.84 mg/L, 7.79 mg/L, and 0.43 mg/L, respectively (Fig. 5**e**, **f**). All indicators were within the corresponding wastewater treatment standards.

At present, there are few reports about the impact of influent fluctuation on the performance of decentralized sewage treatment device according to the discharge characteristics of decentralized sewage in villages, which is very important for decentralized sewage treatment. Munavalli et al. (2022) used an anaerobic baffled reactor (ABR) to analyze the wastewater treatment effect under similar variable flow conditions. They found that the removal rates of COD and NH_4^+-N were only 70%-90% and 40%-65%, and the removal of COD became the bottleneck that restricted the discharge of the entire treatment process. However, the integrated device designed in this study was found to have strong tolerance to instantaneous water and pollutant loads, which can satisfy the needs of decentralized wastewater treatment and reduce infrastructure costs.

2.4. *Variation in the microbial community in each zone of the integrated device*

The inoculated sludge (named S0), the sludge in the anaerobic zone after 180 days (named S1), and the sludge in the aerobic zone (named S2) after 180 days were sampled for microbial community analysis. The alpha diversity index (Table 3) showed that the Shannon index was around 6, indicating that the sludge maintained a diverse microbial community during the treatment. The Ace and Chao indices were both observed to be approximately 2500, indicating that the number of species was high. All the indicators demonstrated that the structure and quantity of the microbial community in the decentralized wastewater treatment system had changed.

At the phylum level, the main phyla in the inoculated sludge included *Bacteroidota* (24.9%), *Proteobacteria* (28.7%), *Firmicutes* (8%), *Chloroflexi* (10.8%), and *Actinobacteriota* (15.6%) (Fig. 6**a**). After 180 days of operation in the decentralized wastewater treatment process, *Bacteroidota* and *Actinobacteriota* were decreased to 14.3% and 13.9% in the anaerobic zone, and 13.4% and 10% in the aerobic zone, respectively. It was reported that *Firmicutes* played an important role in hydrolysis and acidification. For example, it degrades organic matter such as polysaccharides and proteins to generate volatile fatty acids (Ping et al., 2020). In this system, the abundance of *Firmicutes* increased significantly. Its level was 14.2% and 13.1% in the anaerobic and aerobic zones, respectively. The abundance of the *Chloroflexi* phylum also increased significantly, to 17% and 14%, respectively. This indicated that the microbial functional structure of the inoculated sludge had undergone some changes during the operation of the integrated device.

At the genus level, the abundance of *Exiguobacterium* (0.53%, 1.75%, 0.94%), *Eubacterium* (0.4%, 1.16%, 0.4%), and *Acetoanaerobium* (1.39%, 2.48%, 1.7%) increased, all belonging to Firmicutes (Fig. 6**b**). The microbial abundance in the anaer-

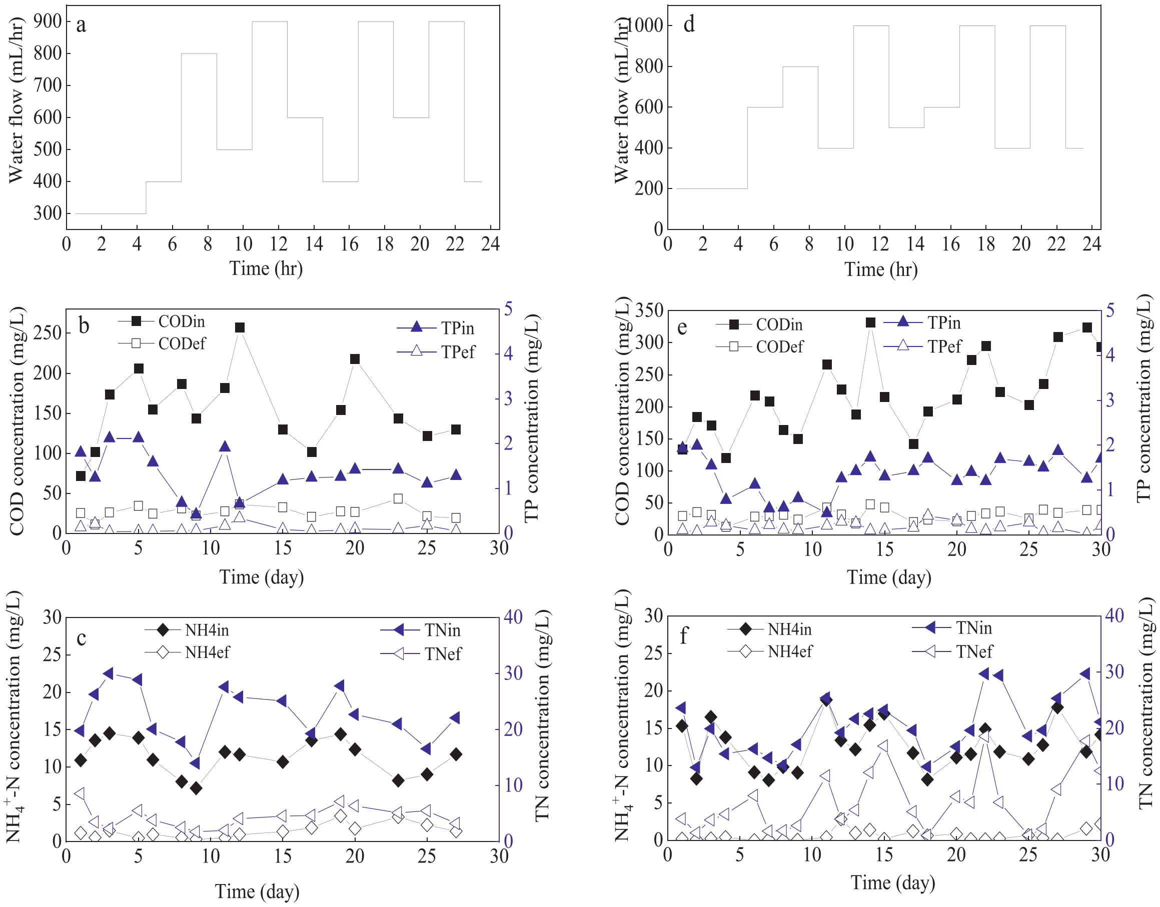

Fig. 5 – The treatment efficiency of the integrated device on decentralized wastewater under non-constant flow rate. a, b and c were mode A, Q_{max}/Q_{min} =3; d, e and f were mode B, Q_{max}/Q_{min} =5.

Table 3 – Bacterial community richness and diversity index of samples at different stages in the reactor.

Sample	Community diversity		Community richness		Coverage
	Shannon	Simpson	Ace	Chao	
S0	6.03	0.007	2537.5	2567.1	0.994
S1	5.99	0.006	2529.4	2533	0.993
S2	6.22	0.004	2469.4	2472.1	0.995

obic zone was significantly higher than that in the aerobic zone. In addition, no *Methanogenium* was found in the system. The observation showed that the sludge had obvious anaerobic digestion in the anaerobic zone, and produced a large amount of bioavailable carbon source. This also provided sufficient carbon source for the nitrogen and phosphorus removal of microorganisms under low load conditions. The abundance of *Nitrosomonas* and *Nitrospira* (Al-Ajeel et al., 2022), which were the ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB), respectively, during the nitrification process, also increased significantly. The *Nitrosomonas* abundance increased from 0.98% (at inoculation) to 1.7% (in the anaerobic zone) and 2.33% (in the aerobic zone). The *Nitrospira* abundance increased from 0.76% (at inoculation) to 1.99% (in the anaerobic zone) and 3.19% (in the aerobic zone). However, compared with that in municipal wastewater, the NH_4^+-N level in the decentralized wastewater was low. The increase in the abundance of AOB and NOB indicated a large source of NH_4^+-N in the system. It was further speculated that the anaerobic digestion of the sludge in the anaerobic zone further released organic nitrogen. The abundance of *Denitratisoma*, a typical PAO with anaerobic phosphorus and aerobic excess phosphorus absorption capacity (Liu et al., 2022), also increased significantly in the system, from 0.14% to 0.78% and 0.83%, respectively. The observation further indicated that this system was highly effective in phosphorus removal, which ensured the efficient enrichment of phosphorus in the anaerobic zone and a compliant phosphorus discharge level. Meanwhile, the abundance of *Geobacter* increased considerably in the system, from 0.13% to 0.63% and 0.5% in the aerobic and anaero-

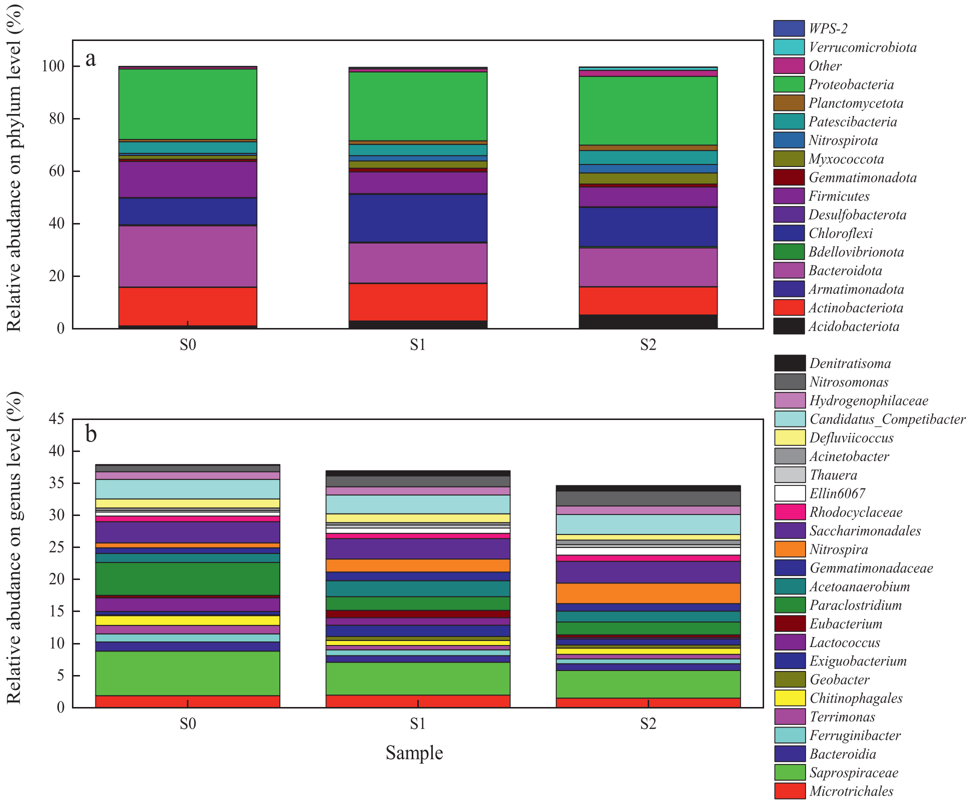

Fig. 6 – The structure and change of the major functioning microorganism community in different zones of the integrated device.

bic zones, respectively. It was speculated that the observation was due to the long-term addition of PAC. As an iron-reducing microorganism that reduces Fe^{3+} to Fe^{2+}, *Geobacter* benefits from the formation of crystals between iron and PO_4^{3-}, so that phosphorus can be recycled (Li et al., 2020; Wen et al., 2022). This provides a better environment for the formation of vivianite by combining Fe^{2+} with PO_4^{3-} under anaerobic conditions (Wilfert et al., 2018; Wu et al., 2021).

3. Conclusions

The decentralized wastewater treatment device with minimal equipment and double self-reflux function has strong resistance to hydraulic and pollutant load shocks. The inflow COD, NH_4^+-N, and TN were in the range of 95–715 mg/L, 7.6–38.5 mg/L, and 9.32–40.3 mg/L, respectively. Discharge compliance can be achieved by shortening the HRT to 0.73 hr under constant flow rate. The airlift reflux improves the removal rate of the total nitrogen, and the removal of phosphorus can also maintain a good level when the air inlet is not higher than 8 m^3/day. In addition, according to the living habits of village residents, the wastewater treatment under an unsteady flow can be realized to reduce the demand for pond capacity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2022.11.005.

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