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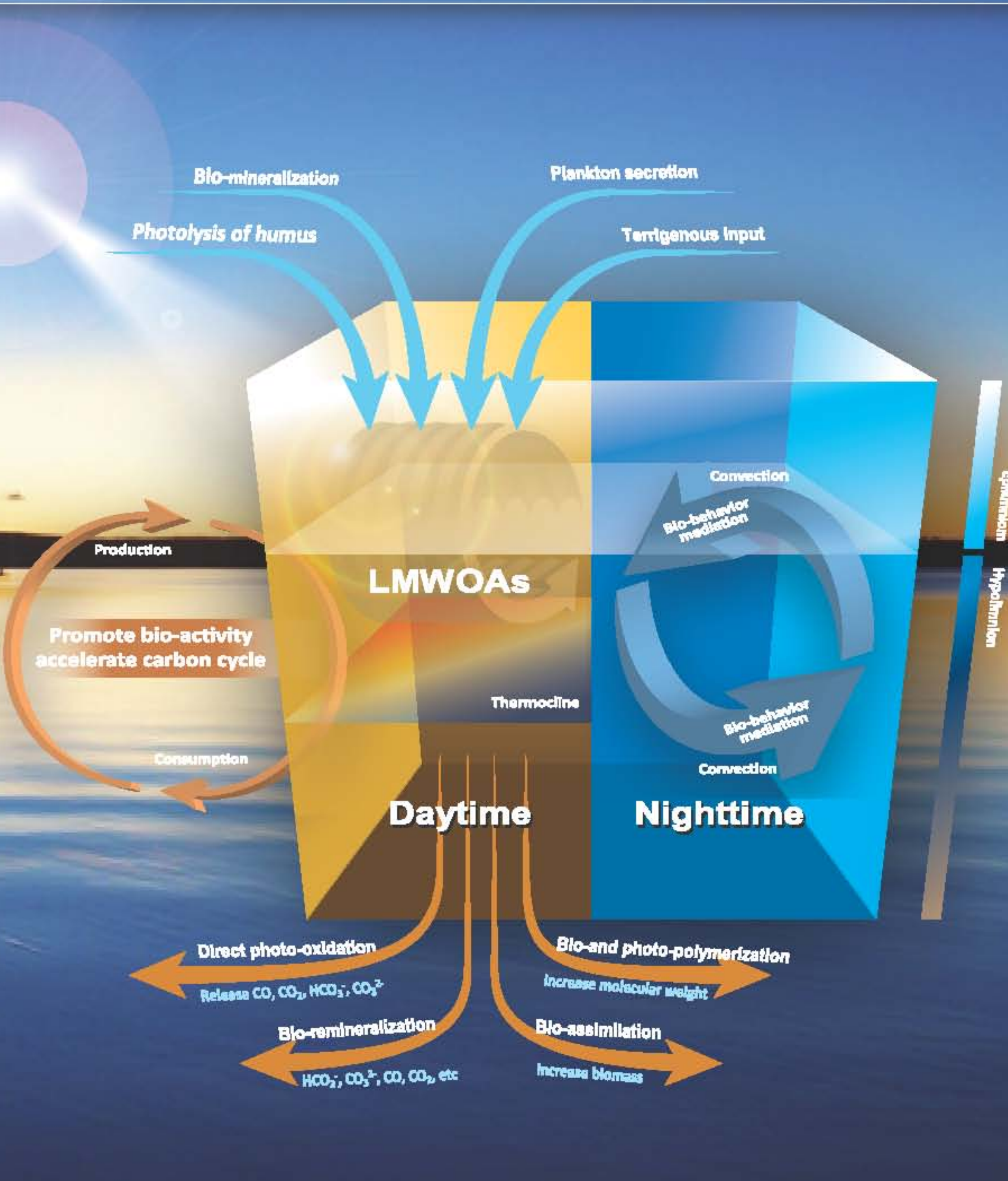

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An innovative integrated system utilizing solar energy as power for the treatment of decentralized wastewater

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Abstract

This article reports an innovative integrated system utilizing solar energy as power for decentralized wastewater treatment, which consists of an oxidation ditch with double channels and a photovoltaic (PV) system without a storage battery. Because the system operates without a storage battery, which can reduce the cost of the PV system, the solar radiation intensity affects the amount of power output from the PV system. To ensure that the power output is sufficient in all different weather conditions, the solar radiation intensity of 78 W/m^2 with 95% confidence interval was defined as a threshold of power output for the PV system according to the monitoring results in this study, and a step power output mode was used to utilize the solar energy as well as possible. The oxidation ditch driven by the PV system without storage battery ran during the day and stopped at night. Therefore, anaerobic, anoxic and aerobic conditions could periodically appear in the oxidation ditch, which was favorable to nitrogen and phosphate removal from the wastewater. The experimental results showed that the system was efficient, achieving average removal efficiencies of 88% COD, 98% NH_4^+-N, 70% TN and 83% TP, under the loading rates of 140 mg COD/(g MLSS·day), 32 mg NH_4^+-N/(g MLSS·day), 44 mg TN/(g MLSS·day) and 5 mg TP/(g MLSS·day).

Key words: solar energy; PV system; wastewater treatment; integrated biological reactor

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Introduction

Biological wastewater treatment facilities, including contact oxidation, oxidation ditch and sequencing batch reactor, are widely used for decentralized wastewater treatment in rural areas worldwide, and are able to effectively remove pollutants such as organic matter, nitrogen and phosphorus from wastewater (Bai and Wu, 2005; Hellstrom and Jonsson, 2003; Liu and Chu, 2007; Quan et al., 2005). However, the facilities face the problem of high electric energy consumption, which results in the consequence that they cannot run stably in rural areas. Therefore, some energy-efficient strategies for wastewater treatment facilities have been suggested (US EPA, 2006). In addition, the development of new energy sources opens new ways of providing power to wastewater treatment facilities.

Solar energy is considered renewable energy. It can be easily transformed to modest levels of power for running electrical equipment through use of a photovoltaic (PV) system (Castaner et al., 2003). The application of solar power in wastewater treatment has generated increasing interest. Current utilization includes the employment of solar power for the treatment of hazardous wastewater through a photo-oxidation process (Pintor et al., 2011; Oyama et al., 2011; Rocha et al., 2011) or photocatalysis (Dillert et al., 1999; Malato et al., 2002; Amat et al., 2005), dewatering of sludge produced from an biological wastewater treatment process through a solar still (Haralambopoulos et al., 2002), and disinfection of water with UV lights powered by the sun (Foster, 2010), etc. However, these forms of solar energy utilization come directly from sunlight. Biological wastewater treatment systems utilizing solar energy as power have been poorly studied. The wastewater discharge locations in rural area are dispersed (Liang et al., 2011). Correspondingly, wastewater treatment facilities are usually built in dispersed mode. Therefore, utilizing solar energy as power for these facilities is suitable, especially in remote areas.

A PV system consists of solar panels, storage batteries, charge controller and inverter, in which the function of the storage batteries is to supply electricity when the sun is not shining (Markvart and Castaner, 2003). These storage batteries must be periodically replaced due to their lifetime

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of 2–3 years, which results in high costs for the PV system and potential pollution of the environment (Armenta-Deu, 2003; Potteau et al., 2003). Besides having decentralized discharge, the wastewater in rural areas has the characteristic of large differences in discharge flow rate for day and night, with often no effluent discharge at night. Therefore, the wastewater treatment facilities can run during the day and stop at night. On the other hand, to remove nitrogen and phosphate from wastewater, anaerobic, anoxic and aerobic conditions are required in the wastewater treatment facilities. Based on these characteristics, it is possible that the wastewater treatment facilities could be driven by a PV system without storage batteries, and the nitrogen and phosphorus removal could be carried out in a single bioreactor, which is run by the PV system under aerobic conditions in the daytime and stopped during nighttime. In the nighttime, anoxic and anaerobic conditions would be able to occur in the bioreactor.

The purpose of this study was to develop an innovative integrated system consisting of a bioreactor and a PV system without a storage battery for decentralized wastewater treatment, and investigate its performance through a lab-scale plant experiment. According to the research results, the optimal modes of energy utilization and the integrated system operation could be established.

1 Materials and methods

1.1 Experimental system and operational conditions

The experimental system consisted of a PV system without storage battery and a bioreactor (**Fig. 1**). The PV system included solar panels, charge controller and inverter. The solar panels had a total surface area of 7.0 m^2, and peak Watts of 780 Wp. The charge controller was able to automatically control the power distribution according to solar radiation intensity. The function of the inverter was to convert direct current to alternating current to satisfy the needs of the electrical equipment.

The bioreactor was an oxidation ditch with double channels 1110 mm in length, 440 mm in width and 1200 mm in depth. The oxidation ditch had a total volume of 240 L, with the volumes of both outer channel and inner channel at 120 L. The diameter and length of the brush in the oxidation ditch were 160 and 120 mm respectively. Dissolved oxygen (DO) and oxidation reduction potential (ORP) sensors were set in the outer channel and inner channel to measure on-line the levels of DO, ORP and pH respectively. The feed pump and the mixers and brushes in the oxidation ditch were driven by the PV system.

The experimental work has been carried out at the Research Center for Eco-Environmental Sciences (RCEES) of the Chinese Academy of Sciences (Beijing, China). The experimental wastewater came from the sewer of RCEES, and its characteristics during the experimental operation are shown in **Table 1**.

This was a laboratory scale experiment. The flow rate of influent in the oxidation ditch was 30–45 L/hr. The operation or stoppage of the oxidation ditch was automatically controlled by the charge controller. When the power output of the solar panels exceeded the maximum predefined threshold of the controller, the feed pump, brush and mixer in the inner channel, and brush and mixer in outer channel ran in that order. When the power output of the solar panels fell below the minimum predefined threshold of the controller, the brush and mixer in the outer channel, brush and mixer in the inner channel, and feed

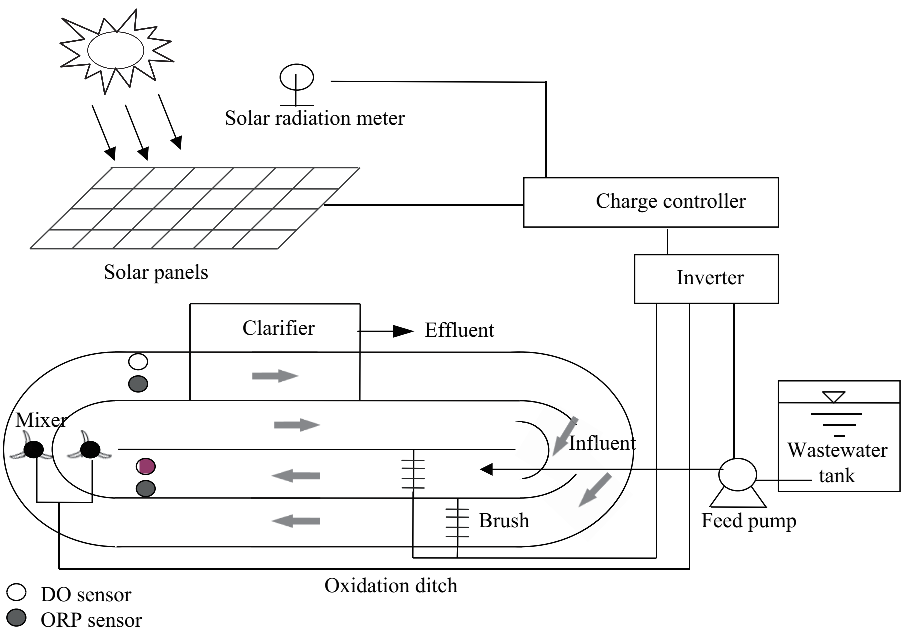

Fig. 1 Schematic diagram of the experimental system.

Table 1 Characteristics of the test wastewater

Parameter	pH	COD (mg/L)	BOD_5 (mg/L)	NH_4^+-N (mg/L)	TN (mg/L)	TP (mg/L)	SS (mg/L)	Temperature (°C)
Average		220	136	49.5	67.7	7.6	152	
Range	6.8–8.1	104–486	69–296	22–77	37–90	1.6–17.2	55–651	13–22

pump stopped in that order.

The seed sludge was obtained from the aeration tank of a local sewage treatment plant. The initial sludge concentration in the experimental oxidation ditch was 2.6 g/L, and it was operated at a sludge retention time of 20 days. During this trial, the mixed liquor suspended solids (MLSS) in the experimental oxidation ditch remained at a concentration of 2.3–4.3 g/L, and the loading rates of COD, NH_4^+-N, TN and TP were 96–179, 21–40, 30–55 and 3–6 mg/(g MLSS·day), respectively.

1.2 Analytical methods

The concentrations of COD, NH_4^+-N, TN, TP and SS in the wastewater, and MLSS in the oxidation ditch, were measured according to the standard methods (CEPB, 2002). The pH was measured with a pH meter. The DO concentration in the oxidation ditch was determined online using DO probes (Advanced HACH LDO Process Dissolved Oxygen Probe). The ORP in the oxidation ditch was determined online using Differential ORP Digital Sensors (GLI DRD1R5) connected to a HACH sc100 Universal Controller (LXV401.52.00002).

The solar radiation intensity was measured by a solar radiation meter (TBQ-2-B, Jinzhou, China) mounted beside the solar panels at the same angle.

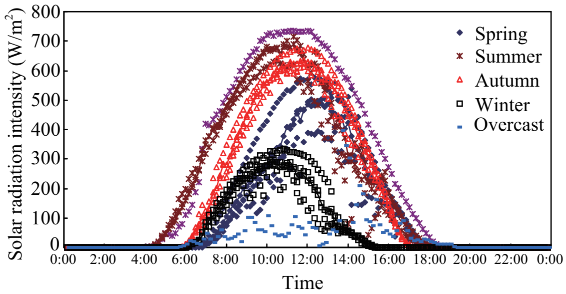

Fig. 2 Variation characteristics of solar radiation intensity in RCEES in different seasons of 2008.

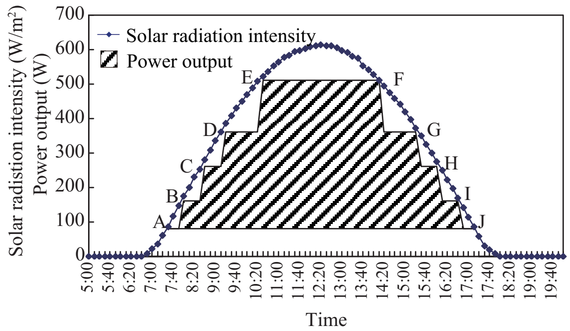

Fig. 3 Profiles of step power output of PV system under variant solar radiation intensity in one day.

2 Results and discussion

2.1 Variation characteristics of solar radiation intensity

It is well known that the intensity of solar radiation at the ground surface varies with the geographic location, the time of day and the season of the year. **Figure 2** shows daily variation characteristics of the solar radiation intensity in RCEES in different seasons. The results indicated that the solar radiation intensity had a peak value at noon, and was 0 during the period from sunset to sunrise the next morning. Naturally, the times of sunrise and sunset and the maximum value of the solar radiation intensity are different in each season. The longest solar radiation time and maximum intensity appeared in summer. In addition, the solar radiation intensity is very low on a cloudy day compared with on a sunny day.

2.2 Power output characteristic and automatic distribution of PV system

The first principle in designing a PV system is that the average daily energy production should slightly exceed the average daily energy consumption of the facilities. The output voltage of solar panels essentially remains constant even as solar radiation intensity is changing, but the amount of current produced by the solar panels is directly proportional to the solar radiation intensity (Foster et al., 2010). In a traditional PV system, the output current is controlled by the batteries. However, the output current of the PV system without batteries can occur only in the daytime, and cannot be stored. In order to utilize the solar energy as well as possible, a step power output mode was used, which was actualized by an automation program installed in the charge controller. The step-height of the step power output was determined by the area of the solar panels and the power consumption of the facilities. **Figure 3** shows a daily variation characteristic of the step power output of the PV system as a function of solar radiation intensity. The power output of the PV system showed a step-increase with the increase of solar radiation intensity (from A to E) in the morning and step-decrease with the decrease of solar radiation intensity (from F to J) in the afternoon. The number of facilities operating depended on the output power of the PV system. The maximum power output occurred during the period from 9:30–14:30. The facilities were fully operational during this time.

To ensure that the power output of the PV system was sufficient in all different weather conditions of the year, as for statistical estimation, a 95% confidence interval of solar radiation intensity is desired. Based on analyzing the observational data of solar radiation intensities in 2008, the solar radiation intensity with 95% confidence was over 78 W/m^2. Therefore, the solar radiation intensity of 78 W/m^2 was determined as the trigger point of power output of the PV system in this study. To avoid frequent on/off switching of the power output at the trigger point due to cloudy weather, a maximum and minimum threshold was predefined in the charge controller.

2.3 Performance of the integrated wastewater treatment system utilizing solar energy as power

The performance of the integrated wastewater treatment system utilizing solar energy as power was investigated. **Figure 4** shows the variation of pollutant concentrations in the oxidation ditch in a 24-hr period. It was found that the concentrations of COD, NH_4^+-N, TN and TP had notable variation between the inner channel and the outer channel. Therefore, the inner and outer channels of the experimental oxidation ditch were simulated with two bioreactors, one high load and one low load, which would benefit enhancing pollutant removal in the inner channel and maintaining the effluent quality in the outer channel. As shown in **Fig. 4**, the effluent concentrations of COD and TP were lower than 23 and 2 mg/L respectively; NH_4^+-N could be completely nitrified, and its effluent concentration was lower than 2 mg/L; TN could be removed in the inner and outer channels respectively, and the effluent TN concentration was about 15 mg/L.

Figure 5a presents the results of COD removal during the operational period of 144 days. The influent COD concentration varied in the range of 104 to 486 mg/L with an average of 220 mg/L, and the effluent COD concentration could be maintained below 30 mg/L. During this study term, COD removal efficiencies averaging 88% with a maximum of 95.5% were obtained, despite the extreme changes in the solar radiation under all climate conditions. During the operational period, average removal efficiencies of 98% NH_4^+-N and 70% TN were obtained (**Fig. 5b**). Even though the TN concentration in the influent varied between 37–90 mg/L with an average of 69 mg/L, the average effluent TN concentration was 21 mg/L, consisting primarily of nitrate. The lack of a biodegradable organic carbon source may be a major factor affecting denitrification efficiency. The influent TP concentration varied in the range of 1.6 to 17.2 mg/L with an average of 7.6 mg/L, and the effluent TP concentration was 0.5–2.0 mg/L with an average of 1.3 mg/L (**Fig. 5c**). The TP removal efficiency of 82.9% was obtained.

3 Conclusions

An innovative integrated wastewater treatment system driven by a PV system without storage batteries was devel-

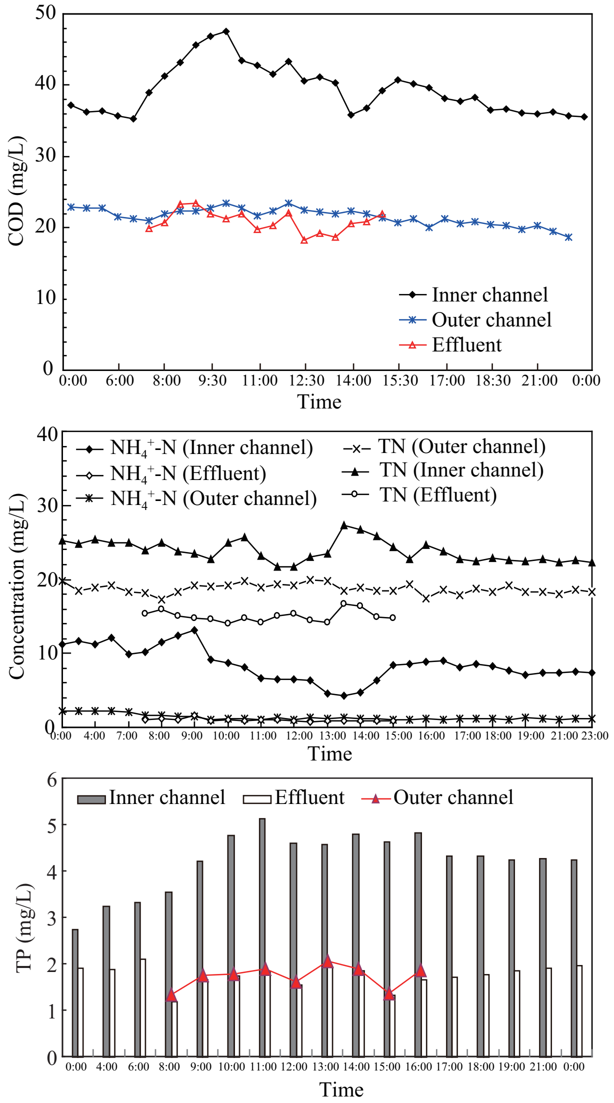

Fig. 4 Variation of pollutant concentrations in the oxidation ditch in a 24-hr period.

oped. The experimental results show that it performed very well for COD, NH_4^+-N, TN and TP removal during the steady operational periods, and their removal efficiencies were measured at 88%, 98%, 70% and 83%, respectively, under the loading rates of 140 mg COD/(g MLSS·day), 32 mg NH_4^+-N/(g MLSS·day), 44 mg TN/(g MLSS·day) and 5 mg TP/(g MLSS·day). The inner and outer channels of the oxidation ditch played two bioreactor functions, which would benefit enhancing pollutant removal in the inner channel and maintaining the effluent quality in the outer channel. The results of monitoring indicated that the solar radiation intensity had a peak value at noon, but its maximum value changed with season and weather. To ensure that the power output of the PV system without storage battery is sufficient in all different weather conditions of the year, a 95% confidence interval of solar radiation intensity is required. In this study, the solar radiation intensity at 95% confidence interval was 78 W/m^2. The step power

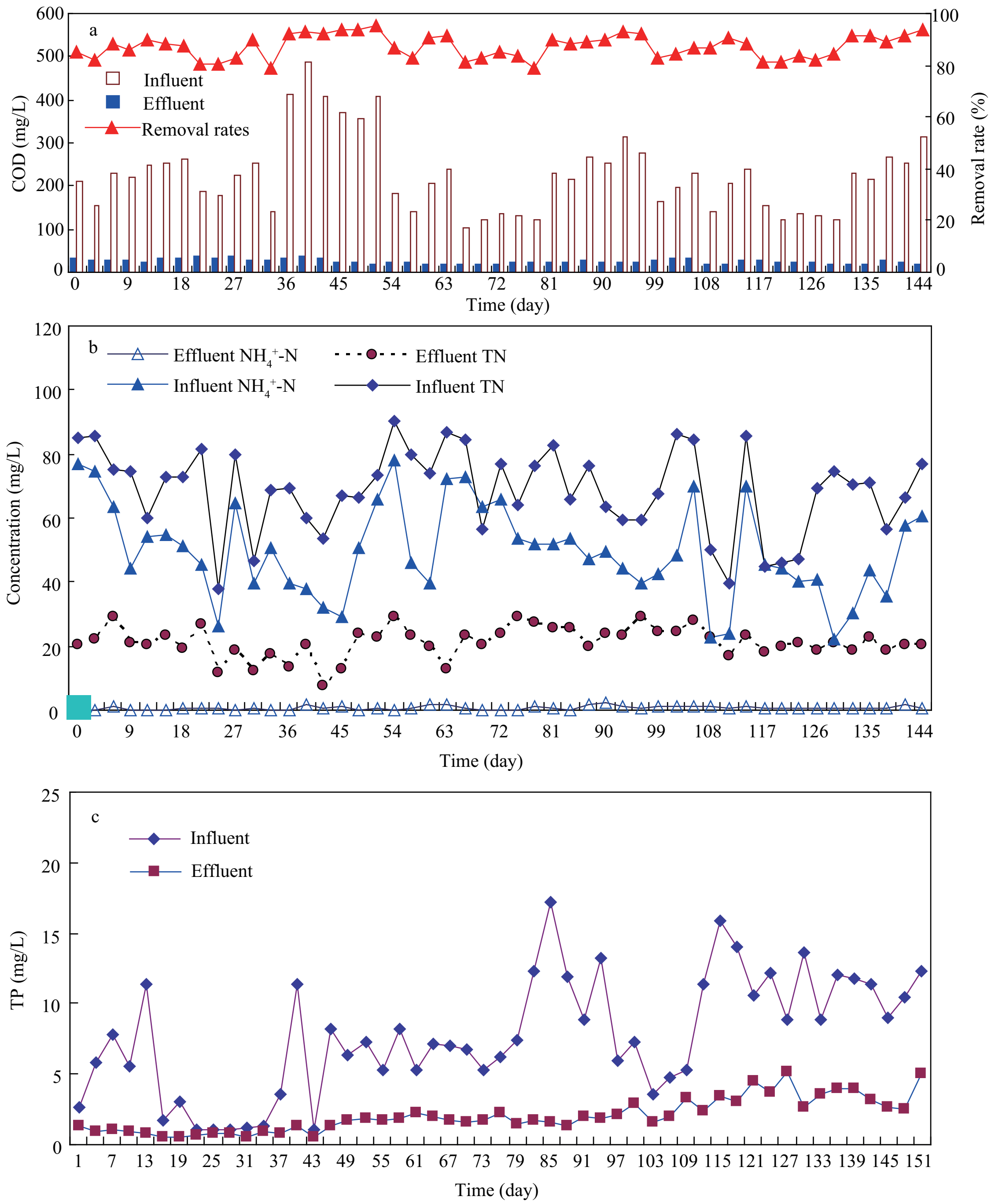

Fig. 5 Removal of COD (a), variation of NH_4^+-N, TN (b), and TP (c) in the influent and effluent.

output mode can utilize the solar energy as well as possible for the PV system without batteries. The operation can be actualized easily by an automation program installed in the charge controller. To avoid frequent on/off switching of the power output at the trigger point due to cloudy weather, a maximum and minimum threshold predefined in the charge controller is essential.

Acknowledgments

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