Original Research

Effects of Unpowered Complex Eco-Technology on Sewage Purification in Central Chinese Rural Areas

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Abstract

Considering the characteristics of rural domestic sewage in central China, an unpowered complex eco-technology composed of anaerobic baffled reactor (ABR), composite soil filling (CSF) system, and free water surface (FWS) constructed wetland was developed to treat rural sewage. The Guogang Village sewage treatment demonstration project at Xinmi City showed that the complex ecosystem had remarkable pollutant removal efficiency. The removal rate was over 90% for chemical oxygen demand and total phosphorus, and over 70% and 80% for TN and NH_4^+-N, respectively. The effluent concentration met the integrated wastewater discharge standard of China (GB18918-2002) level 1B. The complex eco-technology could effectively purify water quality, and it was cheaper and had simpler operation. Thus, it could be considered as an effective method for treating rural domestic sewage.

Keywords: eco-technology, domestic sewage, nitrogen, phosphorus, purifying effect

Introduction

China is experiencing shortages in water resources and faces serious environmental pollution. Thus, accelerating the pace of sewage treatment and increasing the water-recycling rate are imperative. In recent years rural China, which accounts for a vast area, has been facing an increasingly severe situation of water environment protection, especially with the development of the rural economy in China and pollution transfer from urban to rural areas [1]. In 2010, village sewage in China reached about 270 million tons and has continued an upward trend, suggesting that the rural sewage disposal problem needs to be solved urgently. Different from urban sewage, which has perfect collection, treatment technologies and facilities, national laws, and regulations and standards for control, the rural areas of China, which account for nearly 90% of the total area of China, lack drainage and sewage treatment systems [2]. Most sewage in the rural areas of China are directly discharged without treatment because of long-time insufficient attention, shortage of management funds, and weak awareness of rural water environmental protection; this issue has become a major reason for the deterioration of river and lake water quality [3]. Untreated sewage seriously pollutes different types of water resources, leading to the spread and emergence of pathogens, including algal blooms and many other eco-environmental problems [4, 5]. These outcomes seriously affect the health and quality of human life and exacerbate the severe water shortage situation in China. These conditions are contrary to the overall requirements of social development and rural area construction requirements in the new era in China. Water pollution treatment in rural areas will directly affect most Chinese people and the environmental quality of various areas [6, 7].

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Currently, activated sludge treatment technology, which is the most widely used approach, requires significant investment, a long construction period, high energy consumption, and complex operation and management, and thus it is only applicable for the sewage treatment of cities and not dispersed wastewater treatment in the majority of rural areas in central China [8]. Therefore, the development of a dispersed wastewater treatment technology that can be used in the rural areas of central China is very important and necessary.

Complex ecological wastewater treatment technology has high efficiency, low investment, low energy consumption, and easy management [9]. Moreover, it is an effective treatment approach for rural areas, especially for rural areas in central China, which have low temperatures during winter. Based on the experimental data during summer and winter, the aims of this survey were to reveal the wastewater purification effect and continuing stability of the wastewater purification system for the Xinmi project, to explored the key management technology and purification capacity for practical vegetation formation and seasonal turn, and to provided a theoretical basis and technical guidance for the future domestic sewage treatment of rural areas of central China.

Materials and Methods

Process Flow

A complex ecosystem is located 100 m east of Guogang Village, and it was built on a gully without agricultural production value or potential. Domestic sewage flow depends entirely on gravity using terrain height differences to achieve zero power consumption. Considering the local geography, economic and climatic conditions, and the characteristics of dispersed sewage, the current project using unpowered complex eco-technology was composed of an anaerobic baffled reactor (ABR), a composite soil filling (CSF) system, and free water surface (FWS) constructed wetland. Fig. 1 shows a process diagram of the Xinmi project.

Site Description

Fig. 2 shows the project location in China. Guogang Village is located 10 kilometers south of downtown Xinmi in Henan Province of China (113º23'28"E, 34º32'22"N), with a land area of 12 km^2 and a population of more than 3,000. Its public sewer is a combined system. Total sewage

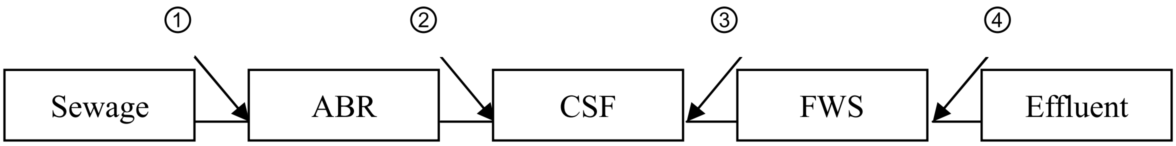

Fig. 1. Process diagram.

Fig. 2. Xinmi project location in China.

treatment has a capacity of 300 m^3/d, and the wastewater treatment system covers a total area of 3,000 m^2 (Fig. 3).

ABR combines the up-flow anaerobic sludge bed and staged heterogeneous anaerobic reactor, which not only greatly increased the complexity and processing efficiency of the anaerobic reactor, but also enhanced the stability of the reactor and its anti-force capability toward external factors (toxic and hazardous substances, high pollution loads, and so on) [10]. The reactor has a simple structure, with characteristics of no short-circuit flow, no blocking, no mixing, and easy start [11]. Based on the characteristics above, the ABR reactor played a very important role in the complex ecosystem, particularly in regulating and homogenizing water quality, reducing the pollution load of CSF and FWS systems, enhancing the biodegradability of wastewater, and removing inorganic materials, among other things. The system was built underneath the surface permafrost layer to ensure its smooth operation during winter.

The CSF system was composed of four treatment cells (every cell with a length of 28 m, a width of 17.5 m and a height of 1.3 m). The section plane structure of each treatment cell is shown in Fig. 4. Anti-seepage treatment was reinforced using geomembrane in this system, and a layer of sand 20 cm thick and 0-2 mm in radius was laid on the geomembrane as a protection layer to prevent piercing. A 10 cm layer of gravel was laid on the sand layer as a hole-prevention measure. Both the wastewater distribution tube and collection tube were placed horizontally in the system inlet. The distance between the distribution and collection tubes was 0.6 m. The composite fillings used in the CSF system of the Xinmi project were mainly obtained from local available resources, including clay eramsite, slag, soil, and corncob. The porosity of composite fillings was 50-65% in the CSF system, and the hydraulic retention time of the CSF system was 4-6 h. The CSF system has several advantages, including low investment, small land occupation, easy management, low operating costs, and no odors that affect the surrounding environment. It attracts more and more domestic and international attention [12]. Compared with the traditional soil infiltration system, the new filler composition greatly increases hydraulic loading, delays system congestion, and improves the purification effect. Its roles can mainly be described in the following areas:

(1) The CSF, built underneath the surface permafrost layer and with good insulation effect, has normal operation even at low temperatures to remove contaminants effectively.
(2) Wastewater has a longer hydraulic retention time in the system, which can effectively purify the water when pollution load is high.
(3) The unique top-down aerobic-anaerobic environment in the filling layer ensures nitrogen removal.

(a) (b) (c)

Fig. 3. (a) ABR system, (b) CSF system, and (c) FWS system in Xinmi project field.

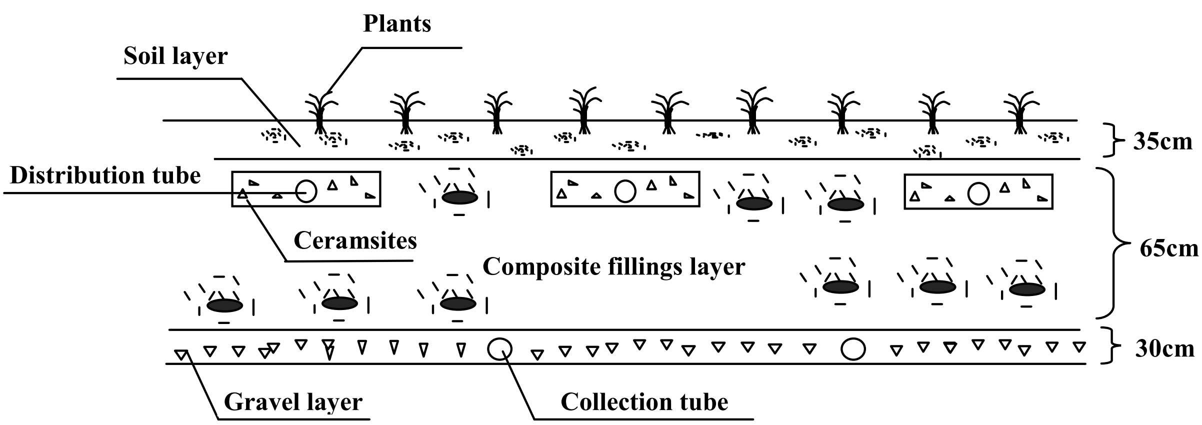

Fig. 4. The section plane structure of the CSF system.

The FWS system was made up of five similar cells. Every cell had a relatively simple structure, with a length of 28 m, a width of 6 m and a water depth of 1.2 m, and the surrounding gradient was 40º. The hydraulic retention time of the FWS system was 3-3.5 d. Emerging aquatic plants grew in a side slope as well as in shallow water (depth less than 0.6 m), and submerged plants grew in water (depth more than 0.6 m). It was a shallow water layer, sunlight can be directly irradiated to the bottom, and oxygen can easily spread, all of which are conducive for the growth of plants and microorganisms. Its construction and operating costs are relatively low, and management is easy [13]. Climatic conditions influence the FWS system, and thus it is often used for level II or level III advanced treatments [14]. Its roles are mainly reflected in the following:

(1) The aerobic-anaerobic micro-environment at the plant roots provides nitrogen removal conditions, and phosphorus is absorbed via matrix and then removed. The nutrient adsorption of plants is also a way for removing phosphorus and nitrogen because of their growth needs [15].

(2) The water-plant system in the FWS provides a habitat for aquatic animals and birds, and thus it beautifies the surrounding environment.

Aquatic plants, including *Typhaangustifolia*, reeds, *Scirpus validus Vahl*, Siberian iris, *Alisma orientale*, *Ceratophyllum demersum*, *Potamogeton crispus*, duckweed, and *Hydrilla verticillata* are cultured in the system to fit in a local environment. Different ecological configuration patterns are used in different processing units.

Water Quality Monitoring Program and Analytical Methods

The major body of the system was completed in mid-June 2010; the system entered debugging and microbial acclimation training phases after. System debugging was completed after 35 days, it was in normal operation in mid-July and continuous every day, and water samples were collected for water quality analysis. Based on the seasonal differences in the living habits of local residents, as well as the impacts of seasonal variations on the external environment, two representative seasons, namely summer (from

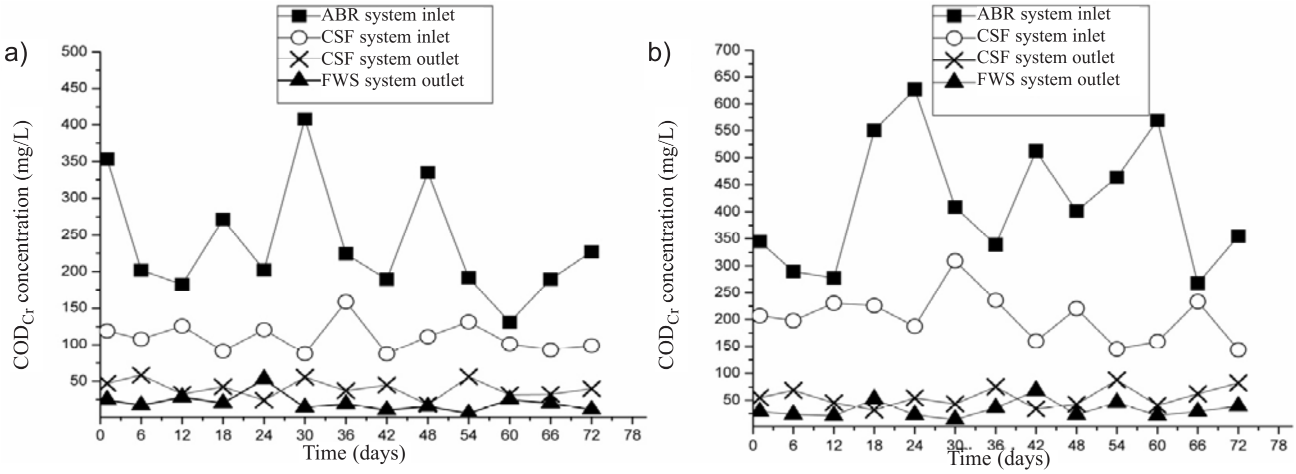

Fig. 5. Changes in CODcr concentrations in summer (a) and winter (b).

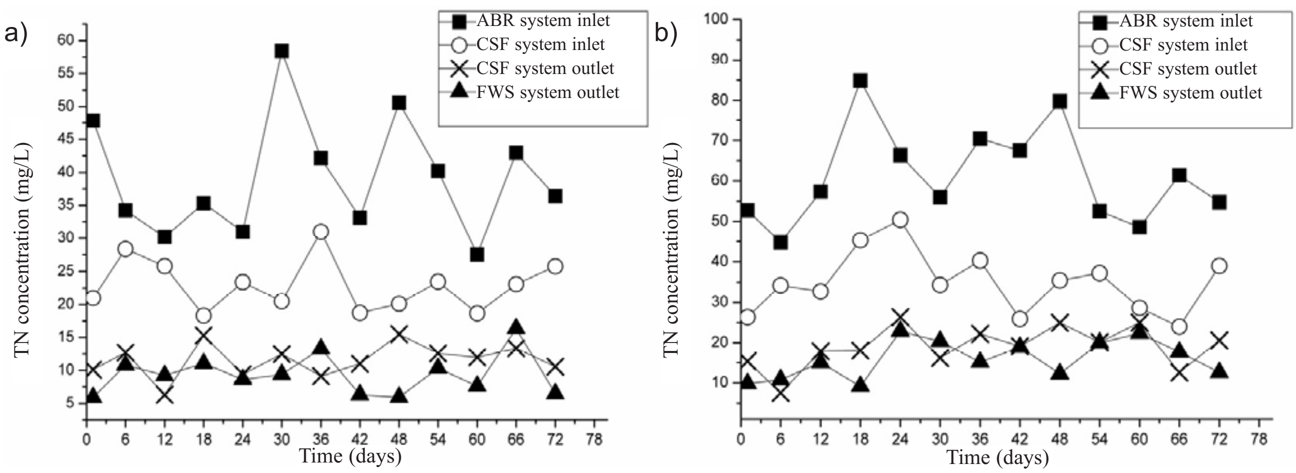

Fig. 6. Changes in TN concentrations in summer (a) and winter (b).

Jul 20 to Oct) and winter (from mid-Dec to Mar), were chosen as monitoring periods, in which water samples were collected to analyze every six days. Sampling points (Fig. 1) were located at the following:
(1) ABR system inlet
(2) CSF system inlet
(3) CSF system outlet
(4) FWS system outlet

A total of four sampling points were used. The water inflow was controlled at 300 m^3/d.

Influent and effluent chemical oxygen demand (COD_{cr}), total nitrogen (TN), ammonia nitrogen (NH_4^+-N), and total phosphorus (TP) were measured using a UV-2450 spectrophotometer (Shimadzu Corporation, Japan) based on the standard methods of potassium dichromate titration, peroxide potassium sulfate ultraviolet spectrophotometry, Nessler reagent spectrophotometry, and potassium persulfate-Mo-Sb digestion anti-spectrophotometry [16]. A Leici JPB-607 dissolved oxygen determinator was used for DO determination. Water quality was assessed according to the Chinese quality of wastewater discharge standard GB 18918-2002 [17].

Results and Discussion

Purifying Effect of the System on COD_{cr}

The COD_{cr} influent concentration during summer was 130-408 mg/L, with an average influent concentration of 239 mg/L and an average effluent concentration of 20 mg/L, as shown in Figs. 5 and 9(a), respectively. The treatment effect was significant in that the average removal rate was 91%. The COD_{cr} influent concentration during winter was 267-627 mg/L, with an average concentration of 415 mg/L, which was higher than the influent concentration during summer. The removal efficiency was slightly lower, and the COD_{cr} influent concentration was significantly higher during winter than during summer. The main reasons for these results might be the dietary habits and reduced bathing water requirement among local residents during winter. Coupled with the lower temperatures, the natural degradation ability decreased during transmission, causing elevated organic matter concentration in the system during winter [18]. These results showed that the ABR had better pollutant removal ability and anti-force capability, making it an important pre-processing structure in the complex eco-system. As the CSF system was built underneath the permafrost layer, the impact of low temperatures during winter on the treatment was not particularly prominent. The FWS was a completely open system, and it was susceptible to external environmental impacts that caused the occasional phenomenon of the COD_{cr} concentration at the outlet being higher than in the FWS inlet [19], but overall, the wetland system exhibited positive effects on COD_{cr} removal.

Purifying Effect of the System on TN and NH_4^+-N

The influent TN concentration had significant seasonal changes because of the influence of the living habits of residents (Figs. 6 and 9 b). The influent TN concentration during winter (with concentration range of 44.8-84.9 mg/L and average concentration of 61.3 mg/L) was higher than that during summer (with concentration range of 27.5-58.4 mg/L and average concentration of 39.2 mg/L). Given that the ABR system was built underground, the structure had good insulation effect, and it could still maintain normal operation even during winter. The TN removal effect was very obvious and stable, and it was less affected by external conditions. The CSF system was also built underground, and thus it had great protection on the activity of nitrification and denitrification bacteria. The TN removal capacity of this processing unit could be improved further if the aerobic-anaerobic environment in the CSF system can be enhanced further [20]. The treatment effect of the FWS system significantly decreased during winter because of changes in temperature [21]. When the whole system treated and purified the sewage, the average TN removal rates were 76 and 74% during summer and winter, respectively, fully meeting the design requirements.

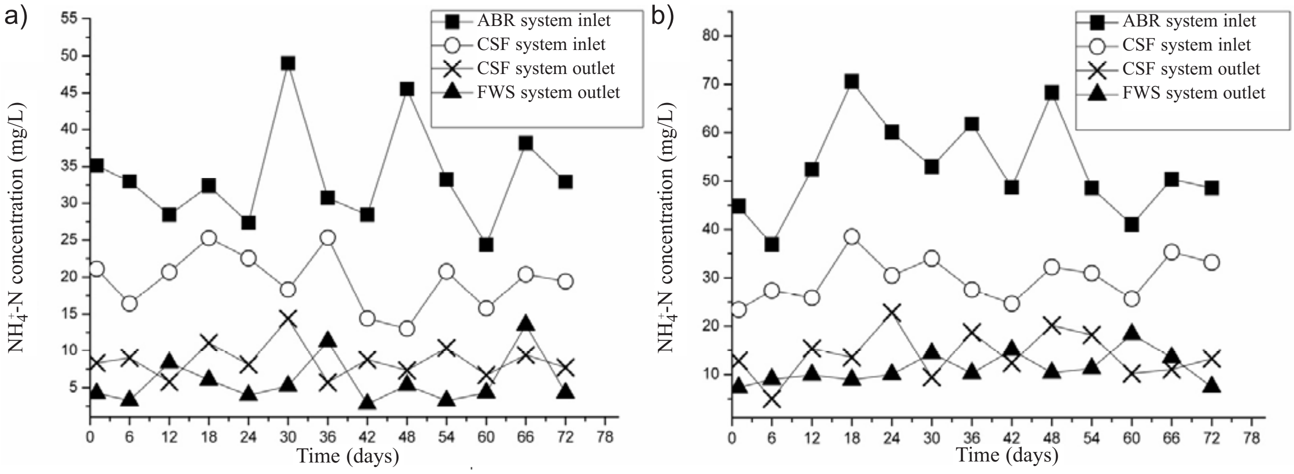

Fig. 7. Changes in NH_4^+-N concentrations in summer (a) and winter (b).

As shown in Figs. 7 and 9(c), the monitoring results indicated that the NH_4^+-N concentration fluctuated with TN concentration. The influent NH_4^+-N concentration during summer was in the range 24.3-48.9 mg/L, with an average concentration of 33.7 mg/L. On the other hand, the influent NH_4^+-N concentration during winter was 36.8-70.6 mg/L, with an average concentration of 52.6 mg/L. The influent NH_4^+-N concentration during winter was much higher than that during summer, and the low temperature led to a slightly higher effluent concentration during winter than during summer. The ABR reactor in the unpowered complex ecosystem was an anaerobic environment; the CSF system was in aerobic condition at the upper part and in anaerobic condition at the lower part; and the FWS system was an aerobic environment [22]. Thus, wastewater underwent equivalent anaerobic-aerobic-anaerobic-aerobic environments

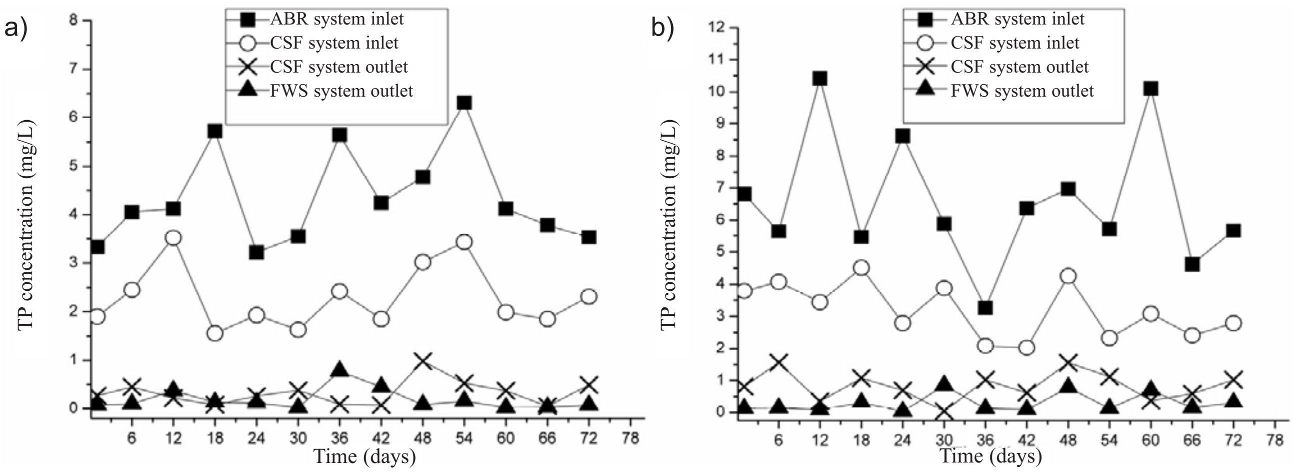

Fig. 8. Changes in TP concentrations in summer (a) and winter (b).

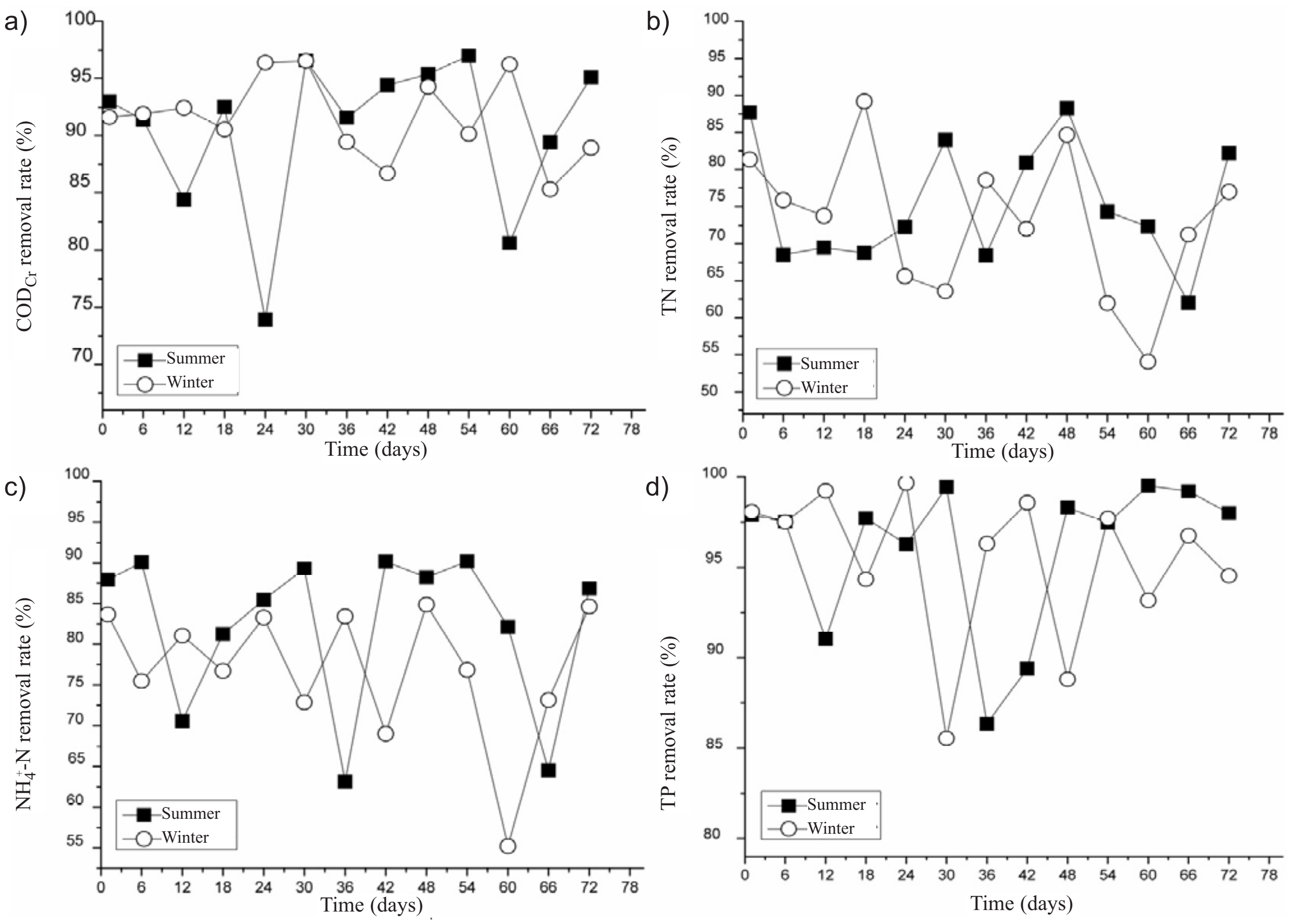

Fig. 9. COD$_{cr}$ (a), TN (b), NH_4^+-N (c), and TP (d) removal rate by the system in summer and winter.

when flowing through the system, providing a series of favorable conditions for nitrogen removal. The organic nitrogen in the ABR system was converted into ammonium nitrogen, part of which was absorbed by anaerobic sludge [23]. The COD in the reactor was also largely removed, which helped improve the dissolved oxygen (DO) content in the wastewater, and the low C/N ratio was conducive to nitrification reaction [24]. Monitoring data showed that the DO concentration was at 0.9-1.5 mg/L, which met the needs of nitrification [25] when it entered the CSF system. Denitrification occurred, and NO_3-N was reduced to N_2 or N_2O when the wastewater flowed to the lower part of the CSF. After entering the FWS system, the NH_4^+-N content in the wastewater further declined through plant absorption, microbial transformation, or its own synthesis and volatilization [26]. After treatment of the complex eco-system, the NH_4^+-N removal efficiency was 80% during both summer and winter.

Purifying Effect of the System on TP

The influent TP concentration during winter was higher than during summer (Figs. 8 and 9 d). The concentrations during summer and winter were 3.2-6.4 and 3.2-10.4 mg/L, with average concentrations of 4.3 and 6.5 mg/L, respectively. The major phosphorus removal mechanisms in wetlands are chemical adsorption, precipitation and plant uptake if wetland vegetation is harvested [27, 28]. The decay of dead aquatic plants and the impacts of external environmental factors in the FWS system generally lead to unstable TP concentrations and their removal [29]. However, the TP is less affected by temperature because the removal of phosphorus is mainly through chemical precipitation [30]. Therefore, the unpowered complex eco-system showed efficient and stable phosphorus removal during both summer and winter. The removal rate was 85-96%, and the effluent TP concentration was less than 1 mg/L.

Comprehensive Purifying Effect of the System

The hydraulic loading of the CSF and FWS systems was 10-15 and 30-35 mm/d, respectively. The unpowered complex eco-system had COD_{cr} and TP removal rates of more than 90%, and the removal rates of TN and NH_4^+-N reached 70 and 80%, respectively. The effluent met the discharge standards (integrated wastewater discharge standard, GB18918-2002, China. Level 1 B: COD ≤ 60 mg/L, TN ≤ 20 mg/L, NH_4^+-N ≤ 15 mg/L, and TP ≤ 1 mg/L). More importantly, the ABR and CSF systems were built underneath the surface permafrost layer to ensure the relatively good treatment effects in winter, when the temperature was low. The efficiency is higher than the domestic surface flow wetlands without the ABR and CSF systems [31], and is even comparable to the treatment effects of serially connected sand filtration and constructed wetland system [32].

In addition, the system was built on a gully without agricultural production value or potential. Domestic sewage flow entirely depended on gravity using terrain height differences to achieve zero power consumption. The environmental, economic, and social benefits of the system were significant. Accordingly, it would probably be a better solution for rural sewage treatment.

Conclusion

The Xinmi project showed that its ABR unit was stable, the pre-processing effect was satisfactory, and management was easy. Moreover, it could effectively reduce the pollution load of follow-up processing units. The CSF unit had an excellent sewage purification effect, which ensured that the final effluent met the discharge standards. The different ecotypes of plants in the FWS unit helped improve the purifying ability of the system. The monitoring results of water quality indicators in system influent and effluent showed that the unpowered complex eco-system had COD_{cr} and TP removal rates of more than 90%, and the removal rates of TN and NH_4^+-N reached 70 and 80%, respectively. This technology had obvious effects, including zero power consumption, superior effluent quality, low investment, and low operating costs during the practical application of the sewage treatment. Moreover, the system can be widely used for the treatment of dispersed sewage in rural areas, attractions, service areas, and other regions. The system showed a positive prospect, especially for sewage treatment in the rural areas of central China during winter.

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