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Original Research

A Modular Coupling System for Efficient Treatment of Rural Domestic Wastewater

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Abstract

Rural domestic sewage has become very serious, while only 17.4% of it is treated centrally or partially, which results in environmental pollution and waste of water resources. To solve this problem, a wastewater treatment system by modular coupling is proposed, and the processing module includes two or three of multi-stage ecological pond, multi-stage drop aeration ecological ditch and multi-stage drop dam. The analysis of three examples shows that the system has a good treatment effect on chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen (NH_4^+-N) and total phosphorus (TP), and the removal ratios are 90.22%, 82.07%, 91.60%, 81.48%, respectively, when the flow rate is 3 m^3/h. After 28 days of continuous operation, the treatment capacity decreases by about 10%, indicating that the system has good long-term treatment performance. The removal ratio decreases slightly under different flow rates, which shows its great adaptability in different hydraulic conditions. In practical application, the system can select different coupling systems according to rural terrain and wastewater quality, and it is suitable for the treatment of rural domestic sewage and agricultural non-point source sewage and the repairment of urban sewage and lake eutrophic water body.

Keywords: ecological restoration, modified natural loofah complex, modular coupling system, removal ratio, rural domestic wastewater, wastewater treatment

Introduction

With the comprehensive treatment of agricultural non-point source pollution, rural domestic sewage has become the main part of non-point source pollution in important water basins [1-3]. As the important part of Rural Revitalization Strategy in China, the treatment of rural domestic wastewater is an important way to improve the rural living environment. He et al. [4] studied the non-point source pollution in Changzhou, China, and the results show that rural domestic sewage was the second largest source of non-point source pollution. Bian et al. [5] pointed out that the rural domestic sewage became the largest source in the

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western region of Taihu Lake Basin, and the emissions of chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen (NH_4^+-N) and total phosphorus (TP) account for 50%, 57%, 85% and 56% of the total emissions respectively, which is shown in Fig. 1. Therefore, the treatment and recycling of rural domestic sewage have attracted extensive attention.

Rural domestic sewage in China mainly includes sewage from kitchen, shower, washing and toilet flushing and rural aquaculture wastewater [6-8]. With the rapid development of economy and the acceleration of the process of urban-rural integration, rural residents' living standards are improving and their lifestyle is closer to the city, which means that the water consumption of rural residents and the discharge of domestic sewage are increasing rapidly [9]. According to the estimation of per capita daily domestic water consumption of 83 liters and discharge coefficient of 0.8, the annual cumulative discharge of rural domestic sewage was about 19.3 billion cubic meters, accounting for about 31% of the total domestic sewage discharge in China. The urban sewage treatment rates in the urban, country and village were 91.9%, 85.22% and 11.4%, respectively. The treatment rate of rural domestic sewage in China is very limited, resulting in environmental pollution and waste of water resources.

Rural sewage treatment mainly includes activated sludge process, oxidation ditch, biofilm process, biological aerated filter, membrane bioreactor, stabilization pond, constructed wetland and others [10-13]. These treatment methods are based on different principles to realize the oxidation, adsorption, solidification/stabilization and isolation of pollutants. Independent treatment methods often have single removal effect or greatly affected by climate, and they are often used in combination in practice [14]. However, the above method has the disadvantages of high cost, unstable removal effect and limited treatment range. A processing system with low cost, stable and efficient treatment effect and wide treatment range requires further study.

Constructed wetlands have received much attention since their great performance in pollutant removal and environmental sustainability [15]. They can remove pollutant through a serious physical, chemical and biological process [16, 17]. Suspended solid pollutant can be precipitated at slow flow rates. The pollutants can also be adsorbed by substrates such as clay or gravel. Plants and microorganisms in a constructed wetland can also adsorb, oxidize or stabilize pollutants through various biochemical reactions. However, traditional constructed wetlands cannot be set up flexibly according to the different scenarios of use, so their application scope has a limitation due to the complex sources of contaminants.

In order to solve the above problems, a new modular coupling wastewater treatment system is proposed to efficiently address pollutants in different scenarios. In practical application, different coupling modes can be selected and combined according to local wastewater quality. Compared with other methods, the system proposed in this paper has significant advantages

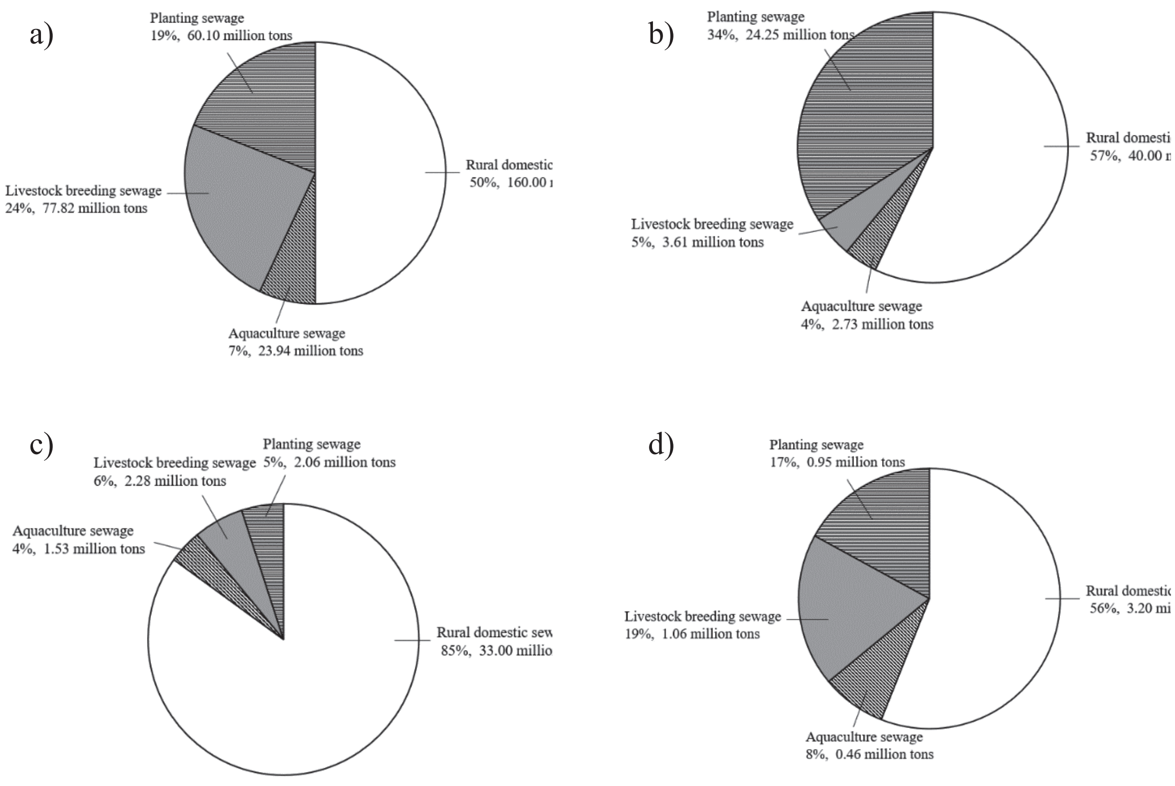

Fig. 1. Proportion of rural domestic sewage in non-point source pollution of Taihu Lake: a) COD, b) TN, c) NH_4^+-N, d) TP.

in high treatment efficient, wide range of application scenarios and low cost.

Materials and Methods

Materials

Wastewater

The wastewater collected from a village in Suqian, China.

Modified Natural Loofah Complex

Natural loofah complex is a natural filler widely existing in nature, and it has been used as a low-cost adsorbent in practice [18]. It is prepared into superhydrophobic material through modification treatment to reduce hydroxyl to reduce hydrophilicity and continuously supply carbon source and prolong its service life in water. It can also improve the biofilm hanging performance of loofah complex filler [19]. The loofah complex can provide sufficient carbon source in the process of nitrogen and phosphorus removal. By modifying the loofah complex, the surface structure can be changed and the adsorption performance can be improved. What is more, the modified loofah complex filler is an efficient adsorption material for pollutants such as nitrogen and phosphorus in water. The degradation of microorganisms and the adsorption of the modified loofah complex can achieve the dynamic system of adsorption-desorption, which can effectively solve the disadvantage that ordinary adsorption materials cannot effectively intercept pollutants after adsorption saturation. Moreover, the modified loofah complex filler also has the characteristics of convenient material acquisition, low price and environment protection.

Natural loofah complex was washed with deionized water to remove surface impurities. Under the condition of water bath at 25ºC, the natural loofah complex was socked in 1 mol/L NaOH solution for 30 min. After soaking, the natural loofah complex was rinsed with deionized water to neutral. At this time, the natural loofah complex completed the modification process.

Emergent Plants Planted in Biological Stabilization Ponds

The carrier of emergent plants in the biological stabilization pond is an ecological floating bed filled with modified loofah complex, and the filling rate is 50%. The emergent plant selected in the experiment was *Oenanthe javanica* (Blume) DC. The combined utilization of modified loofah complex and emergent plant can overcome the shortcomings faced by the single means of plant purification and the seasonal problems of plants, ensures the stability of wastewater treatment effect, and form an artificial ecosystem by planting aquatic plants and aquaculture of aquatic and waterfowl in the pond [20-22]. Driven by solar energy (solar radiation provides energy) as the initial energy, the organic pollutants entering the wastewater in the pond are degraded and transformed through the material migration and transformation of multiple food chains and energy in the ecological stability pond.

Submerged Plants Planted in Submerged Culvert Oxygen Pond

Submerged plants are planted in submerged culvert oxygen pond. The submerged plants can be selected if it is suitable for local growth. The submerged plant in the experiment was *Hydrilla verticillate* (Linn. f.) Royle. In the submerged oxygen culvert pond, the photosynthetic and respiratory effects of submerged plants are used to build an ecological food chain system to realize the deep purification of water quality.

Devices

The modular coupled wastewater treatment system includes two or three of multi-stage ecological pond, multi-stage drop aeration ecological ditch and multi-stage drop dam, which can be connected in series arbitrarily in the actual use process. The multi-stage ecological pond and the multi-stage drop aeration ecological ditch are connected in series; or the multi-stage drop dam, the multi-stage ecological pond and the multi-stage drop aeration ecological ditch are connected in series; or the multi-stage drop aeration ecological ditch, the multi-stage ecological pond and the multi-stage drop dam are connected in series. The photo of the devices is shown in Fig. 2.

The contact oxidation pond, the biological stabilization pond and the submerged culvert oxygen pond are interconnected in the multi-stage ecological pond. The upper height of the diaphragm between the contact oxidation pond and the biological stabilization pond is flush with the height around the multi-stage

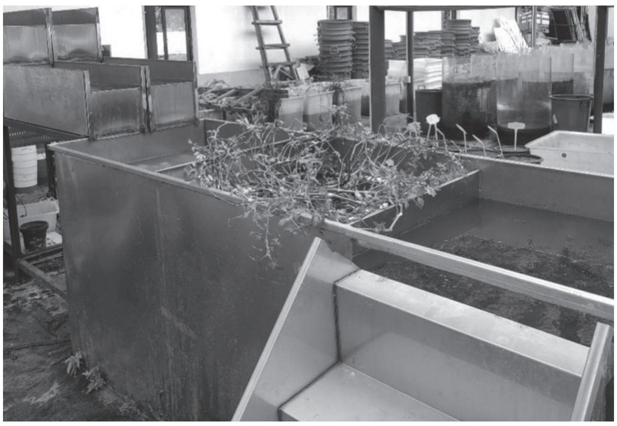

Fig. 2. Photo of devices.

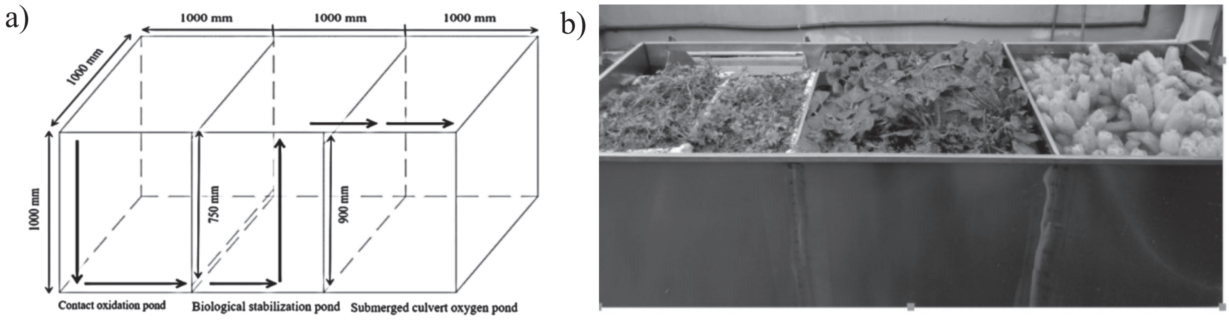

Fig. 3. Images of multi-stage ecological pond: a) Structural diagram of multi-stage ecological pond, b) Photo of multi-stage ecological pond.

ecological pond. An opening is designed at the bottom of the diaphragm to pass through the water flow, and this can connect the slow-release filler in the contact oxidation pond and the biological stabilization pond, and the aquatic plants in the floating bed and the polluted water body. The height of the partition between the biological stabilization pond and the submerged culvert oxygen pond is 10-20 cm lower than the height around the multi-stage ecological pond. Thus, the water in the biological stabilization pond overflows from the partition into the submerged culvert oxygen pond, which can reduce the impurities such as particulate matter entering the submerged culvert oxygen pond. The specific size of the contact oxidation pond, biological stabilization pond and submerged culvert oxygen pond can be adjusted according to the water treatment capacity and geographical location. The structure and photo of the multi-stage ecological pond are shown in Fig. 3. The contact oxidation pond, biological stabilization pond and submerged culvert oxygen pond are successively from left to right, and the arrow indicates the direction of water flow.

Pebbles are paved in the multi-stage falling drop aeration ecological ditch which is shown in Fig. 4. The thickness of pebbles paved in a single ecological ditch is 4–6 cm. In the examples, the diameter of pebbles is 2–3 cm. After multi-stage falling drop aeration ecological ditch, it is convenient for biofilm to reproduce and grow on pebbles. It is also preferred to plant aquatic plants at the connection of two ecological ditches and at the place with slow water flow to form multi-functional water drop oxygenation and ecological ditches, strengthen the purification effect, beautify the environment and increase economic benefits. The length, width and height of a single ecological ditch are 1000 mm, 800 mm and 500 mm. It is an open cuboid. The height of the stainless-steel plate at the connection of the two ecological ditches is preferably lower than that of the other three sides to facilitate the flow of water.

Multi-stage drop dams can be built according to rural terrain and flow through drop steps by the gravity of water to achieve the effect of multi-stage drop and oxygen enrichment. As a specific embodiment of the experiment, the size and photo of the multi-stage drop dam is shown in Fig. 5.

Methods

Water quality indicators include chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen (NH_4^+-N) and total phosphorus (TP). COD was determined using acidic potassium permanganate method. TN was determined using alkaline potassium persulfate digestion-UV spectrophotometry (HJ636-

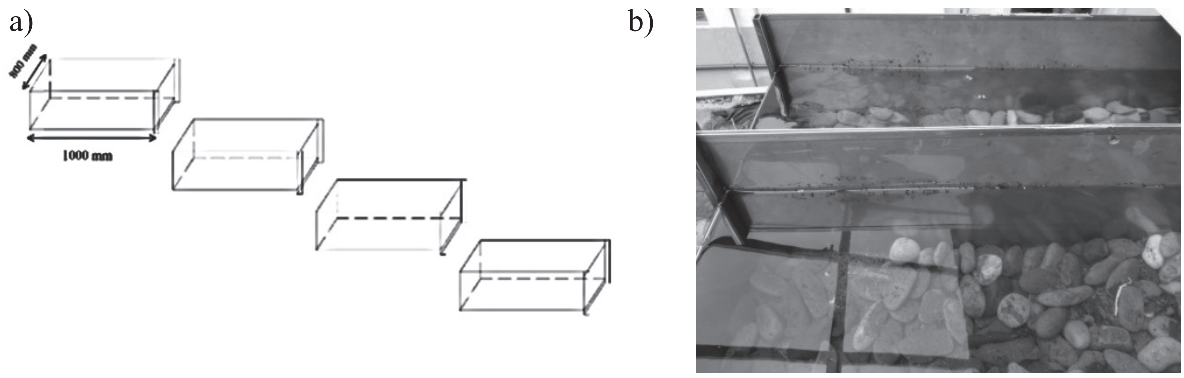

Fig. 4. Images of multi-stage drop aeration ecological ditch: a) Structural diagram of multi-stage drop aeration ecological ditch, b) Photo of multi-stage drop aeration ecological ditch.

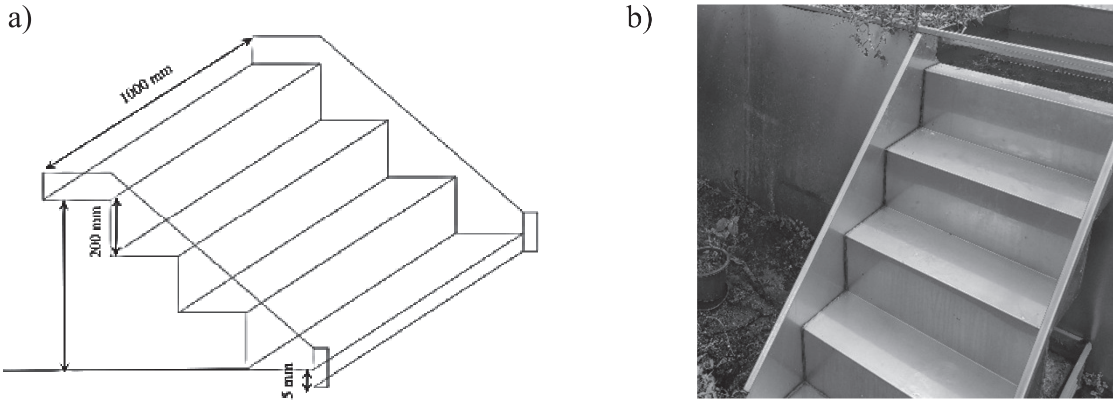

Fig. 5. Structural diagram of a multi-stage drop dam: a) Structural diagram of multi-stage drop dam, b) Photo of multi-stage drop dam.

2012, China) and TP was determined using ammonium molybdate spectrophotometry (GB11893-89, China). Concentrations of NH_4^+-N were measured by Naismith spectrophotometry with a medium range of portable photometer (HI96715, China) and a low range of portable photometers (HI96728, China; HI96707, China) (HANNA Instruments, USA).

Example Design

Example 1

The multi-stage ecological pond and multi-stage drop oxygenation ecological ditch are connected in series, and the structural diagram is shown in Fig. 6. In this coupling system, the submerged water conservation pond of the multi-stage ecological pond is connected with the multi-stage drop water oxygenation ecological ditch, and the side of the submerged water culvert oxygen pond is provided with a water outlet to flow out of the water supply flow and downstream along the multi-stage drop water oxygenation ecological ditch. In this coupling system, the multi-stage ecological pond can effectively purify the water quality and block part of nitrogen and phosphorus. It can also beautify the ecological environment and improve the water quality conditions of rural circulating water. At the same time, it can be used as a regulating pond to regulate the change of water volume, which solves the lack of regulating pond in the traditional ecological ditch system and the large fluctuation of wastewater volume in modern villages. Normal precipitation will lead to the increase of surface runoff and the overflow of nutrient elements such as nitrogen and phosphorus to different canal sections of ecological ditches, resulting in poor treatment effect and other problems. The coupling system is suitable for eutrophic water with large fluctuation of water quantity.

The multi-functional ecological pond includes contact oxidation pond, biological stability pond and submerged culvert oxygen pond, and the size of each pond is 1.0 m × 1.0 m× 1.0m , the height of the diaphragm between the contact oxidation pond and the biological stabilization pond is flush with the height around the multi-stage ecological pond, an opening with a height of 25 cm is opened below the diaphragm, and the height of the diaphragm of the biological stabilization pond and the submerged culvert oxygen pond is 90 cm.

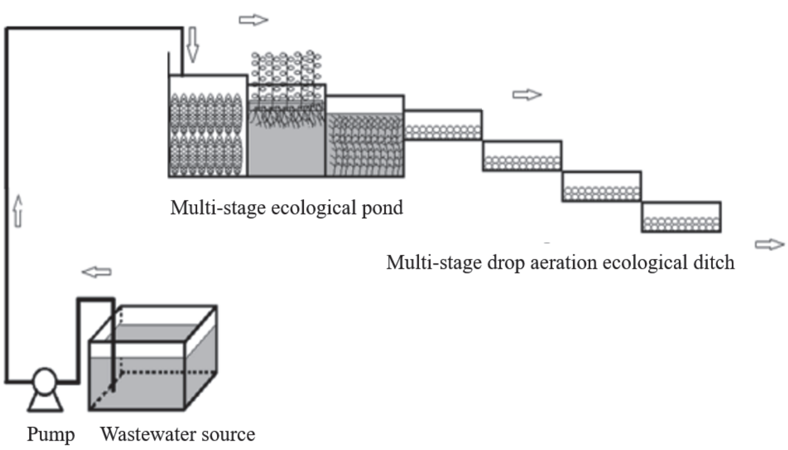

Fig. 6. Structural diagram of example 1.

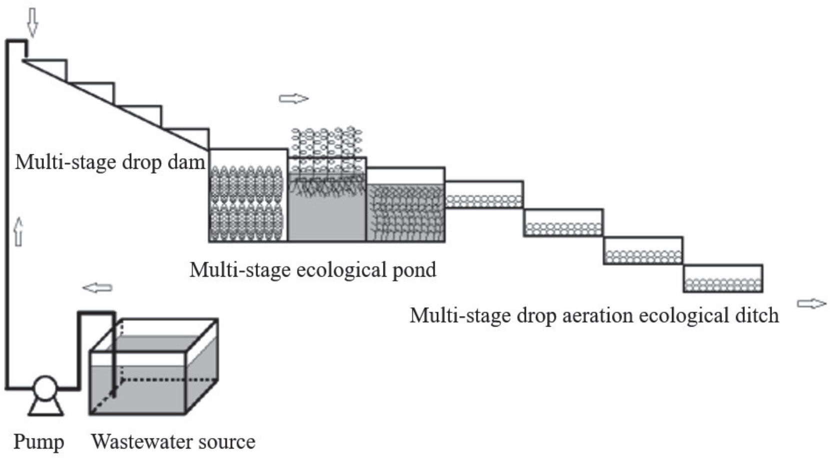

Fig. 7. Structural diagram of example 2.

The stages of multi-stage falling water oxygenation ecological ditches are 4 levels. Each ditch is an open cuboid with a length of 1000 mm, a width of 800 mm and a height of 500 mm processed from stainless steel plate. The four ditches are nested from top to bottom to form a 4-level falling water oxygenation ecological ditch.

Example 2

The multi-stage drop dam, multi-stage ecological pond and multi-stage drop aeration ecological ditch are connected, and the structural diagram is shown in Fig. 7. The multi-stage drop dam is connected with the contact oxidation pond of the multi-stage ecological pond. The water flows down from the multi-stage drop dam by gravity to enrich oxygen, flows into the multi-stage ecological pond for nitrogen and phosphorus removal, and then flows out of the multi-stage ecological pond into the multi-stage drop aeration ecological ditch for further contact oxidation. This coupling system is suitable for mountainous and rural areas with steep terrain, which can drop the water down, increase the dissolved oxygen in the water body, and drop the water flow to the ecological ditch. After being intercepted and degraded by the multi-stage ecological pond, the multi-stage drop aeration ecological ditch can guide the water flow.

The multi-stage drop dam, multi-stage ecological pond and multi-stage drop aeration ecological ditch are connected in series for wastewater treatment. The multi-stage drop dam has three stages, the step height is 200 mm, the width is 1000 mm, and the total height of the multi-stage drop dam is 600 mm. The size and other setting conditions of multi-stage ecological pond and multi-stage drop oxygenation ecological ditch are consistent with example 1.

Example 3

The multi-stage drop aeration ecological ditch, multi-stage ecological pond and multi-stage drop dam are connected in series in turn, and the structural diagram is shown in Fig. 8. In this coupling system, the multi-

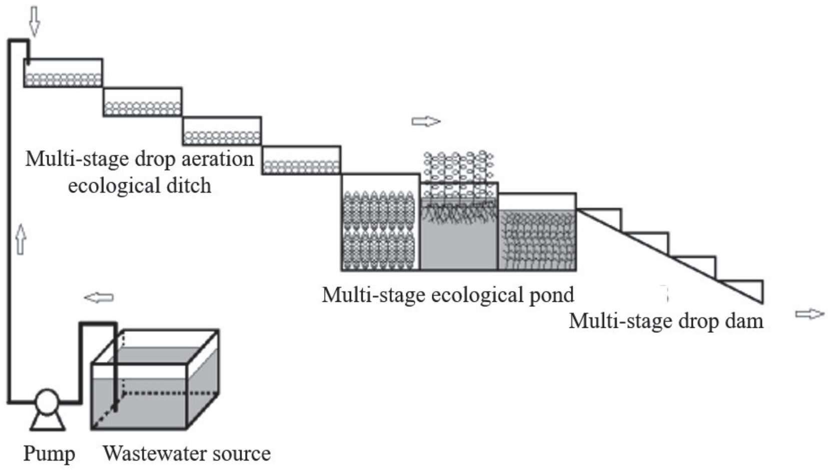

Fig. 8. Structural diagram of example 3.

level drop aeration ecological ditch is connected with the contact oxidation pond of the multi-level ecological pond, and the submerged culvert oxygen pond of the multi-level ecological pond is connected with the multi-level drop dam. The water flows through the multi-level drop aeration ecological ditch for contact oxidation to remove the organic matter in the wastewater, and then flows into the multi-level ecological pond for nitrogen and phosphorus removal. It flows out of the multi-stage ecological pond and into the multi-stage drop dam for further oxygen enrichment and organic matter removal. This coupling system is suitable for the situation that the water volume changes little but the site is limited. The ecological ditch is used for water flow guidance and primary purification, and then it is intercepted and degraded by multi-stage ecological pond and multi-stage falling dam in turn to increase the dissolved oxygen and visual beauty of the water body.

The multi-stage drop aeration ecological ditch, multi-stage ecological pond and multi-stage drop dam are connected in series for wastewater treatment. The setting parameters such as the size of multi-stage drop aeration ecological ditch, multi-stage ecological pond and multi-stage drop dam are consistent with example 2.

Results and Discussion

Removal Effect at Different Distances

In order to compare the treatment effects of different examples on wastewater, experiments were carried out under the flow rate of 3 m^3/h. The effluent quality is analyzed after 7 days, and the results are shown in Fig. 9. The waste water in the experiments was taken from rural area in China, so the composition of pollutants varied depending on the daily life activities of villages. This does not affect the experimental results, as it better reflects the performance of the system in actual wastewater treatment. After treatment, the removal rates of COD, TN, NH_4^+-N and TP in wastewater are very significant. With the increase of horizontal distance, the content of pollutants decreases gradually, and the removal ratio is more than 70%, which shows that the system has excellent treatment effect. For example 1 and example 3, at the beginning of the curve, the slope is very high, and the slope gradually decreases with the increase of distance. In the initial stage, adsorption, oxidation and other reactions can occur to pollutants, and the pollutant concentration in the initial stage is higher, which makes the reaction speed very fast. For example 1 and example 3, their curvatures

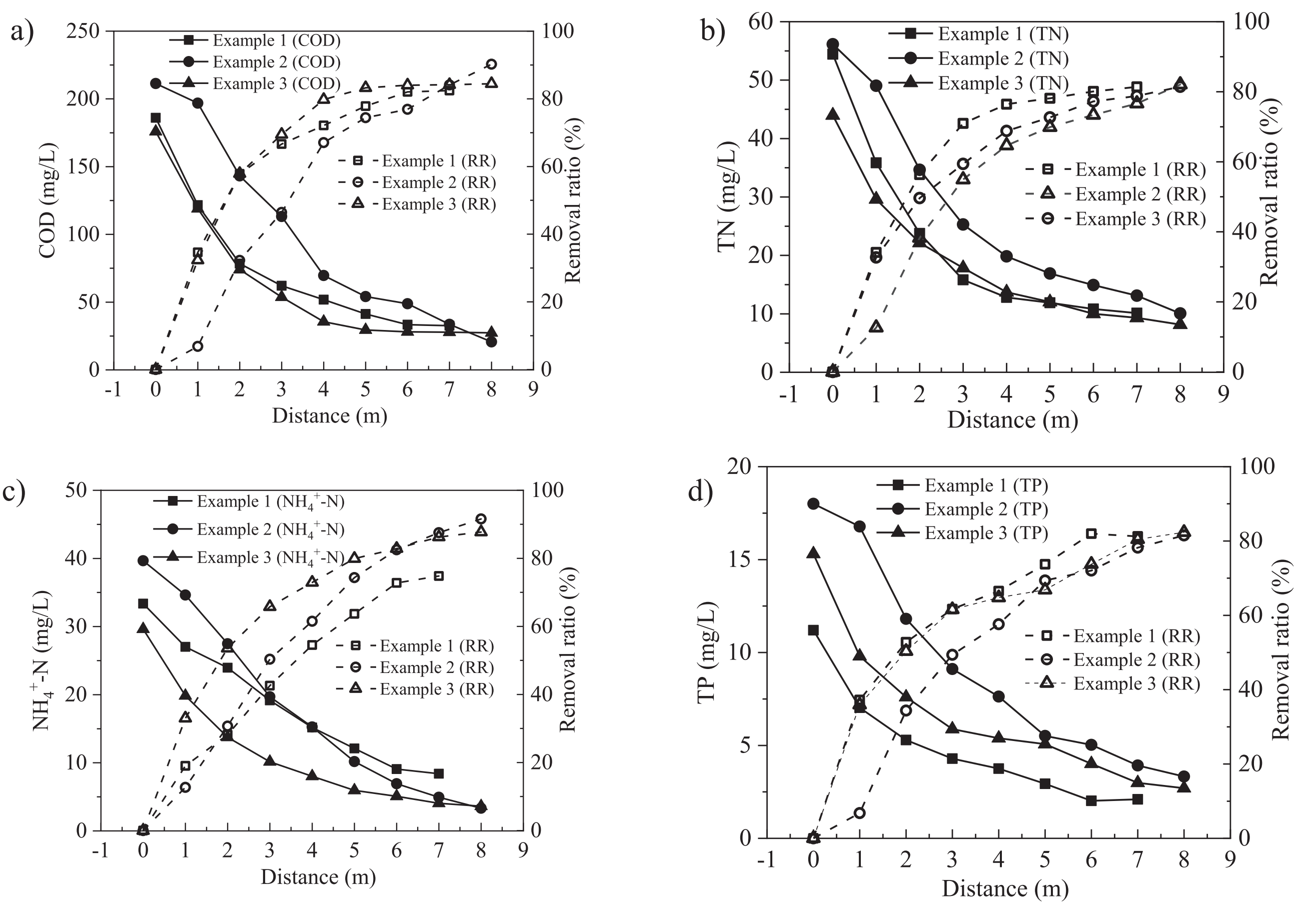

Fig. 9. Removal effect at different distances: a) COD, b) TN, c) NH_4^+-N, d) TP.

are very close at the initial stage, which means that they are both a combination of the multi-stage drop aeration ecological ditch and multi-stage ecological pond, so they have similar processing efficiency and speed. Example 2 has a lower initial slope than example 1 and example 3, which means that its initial reaction speed is slow. The initial part of example 2 is the multi-stage drop dam, which does not contain aquatic plants or chemicals that can purify wastewater. Therefore, wastewater is mainly removed by oxidation, resulting in poor initial removal effect. Comparing the curves of different cases, it can be found that the outlet concentration is very small and very close, which indicates that the processing capacity of the system is far from reaching the upper limit of its capacity, and various combinations have good processing effects. This is because the treatment of pollutants is mainly realized by the multi-stage drop aeration ecological ditch and multi-stage ecological pond which is included in three examples. Thus, the final effect is very excellent. By comparing three different examples, it is found that example 2 is the best for the treatment of various pollutants.

Removal Effect under Different Duration

In order to further evaluate the long-term service performance of the system, the inlet pollution concentration, outlet pollution concentration and pollutant removal ratio at different time were tested at a flow rate of 3 m^3/h, as shown in Fig. 10. Due to the different daily pollution concentration, the removal ratio is more comparable and meaningful. The results show that the concentrations of the four pollutants decrease with time, indicating that the treatment capacity of the system has a limit. Compared with three systems, example 2 maintained the best treatment effect. The treatment efficiency of ammonia nitrogen decreases significantly after 28 days. Considering that the pollutant concentration at the inlet is very low at this time, the calculation result of removal ratio may be errors. For different pollutants, TP decreased most significantly with time, while the removal ratio for the other three pollutants decreases by about 10%. Therefore, it can be considered that the system has good long-term treatment performance.

Removal Effect under Different Flow Rates

The increase of flow rate means the decrease of reaction time, which reduces the removal effect. Under different flow rates, the removal effect is close, which indicates that the system has good removal effect under various flow rates. Comparing the three examples, it is found that the removal effect of example 2 is the best and that of example 1 is the worst, especially for COD. The important way of COD removal is oxidative decomposition, and the longer path in example 2 means the increase of the oxidation time. Comprehensive

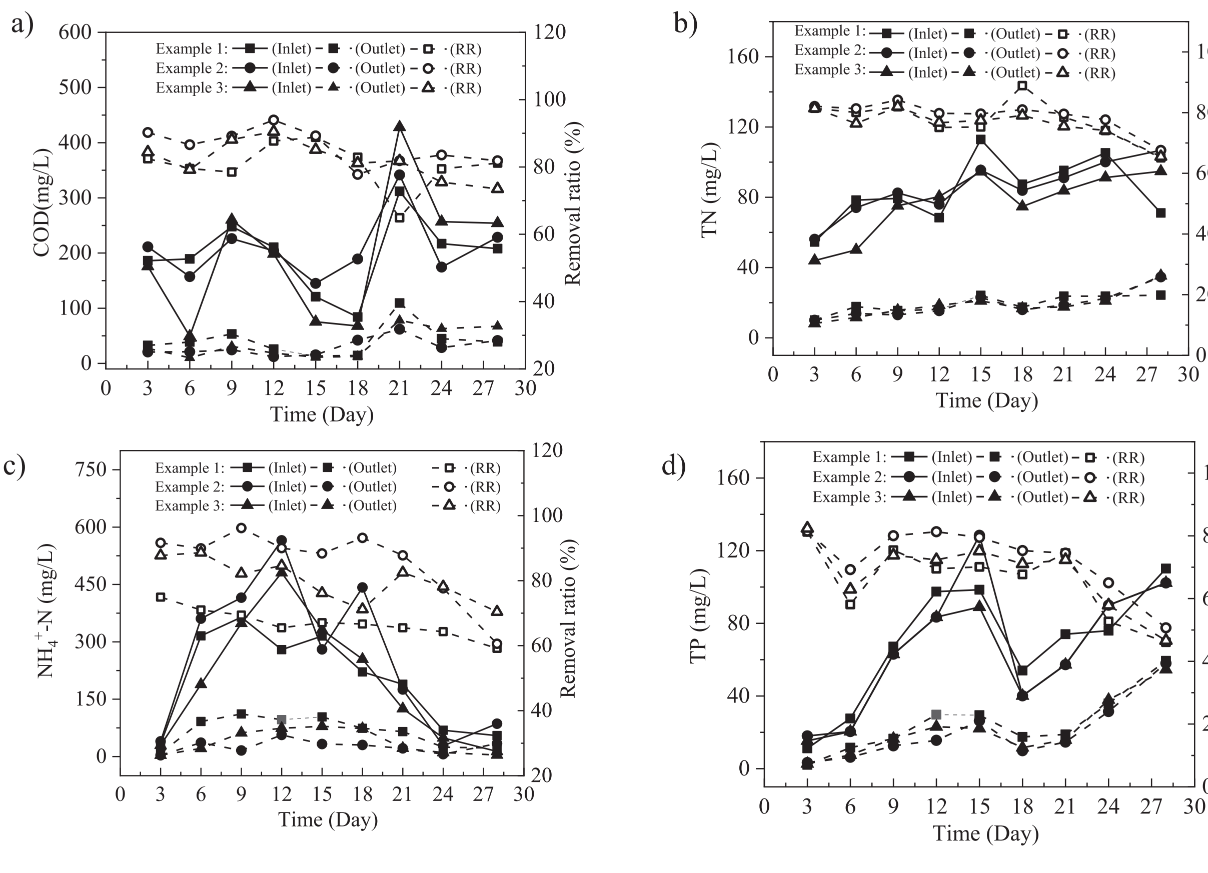

Fig. 10. Removal effect at different time: a) COD, b) TN, c) NH_4^+-N, d) TP.

Table 1. Removal effect under different flow rates.

		Example 1			Example 2			Example 3		
COD	Flow rate (m^3/h)	Inlet (mg/L)	Outlet (mg/L)	RR (%)	Inlet (mg/L)	Outlet (mg/L)	RR (%)	Inlet (mg/L)	Outlet (mg/L)	RR (%)
	3	186.00	32.67	82.44	211.33	20.67	90.22	175.86	27.33	84.41
	6	207.67	42.67	79.45	192.03	21.00	89.06	161.67	27.33	83.09
	9	220.65	50.00	77.34	209.23	28.94	86.17	187.23	33.81	81.94
		Example 1			Example 2			Example 3		
TN	Flow rate (m^3/h)	Inlet (mg/L)	Outlet (mg/L)	RR (%)	Inlet (mg/L)	Outlet (mg/L)	RR (%)	Inlet (mg/L)	Outlet (mg/L)	RR (%)
	3	54.53	10.13	81.42	56.13	10.07	82.07	43.97	8.17	81.42
	6	60.80	12.50	79.44	47.30	9.43	80.06	41.39	8.33	79.85
	9	62.10	14.13	77.25	52.34	10.50	79.93	42.32	9.16	78.36
		Example 1			Example 2			Example 3		
NH_4^+-N	Flow rate (m^3/h)	Inlet (mg/L)	Outlet (mg/L)	RR (%)	Inlet (mg/L)	Outlet (mg/L)	RR (%)	Inlet (mg/L)	Outlet (mg/L)	RR (%)
	3	33.37	8.40	74.83	39.67	3.33	91.60	29.63	3.63	87.74
	6	45.23	11.87	73.77	35.43	3.43	90.31	28.40	3.97	86.03
	9	44.29	12.06	72.76	36.23	3.58	90.11	30.21	4.31	85.72
		Example 1			Example 2			Example 3		
TP	Flow rate (m^3/h)	Inlet (mg/L)	Outlet (mg/L)	RR (%)	Inlet (mg/L)	Outlet (mg/L)	RR (%)	Inlet (mg/L)	Outlet (mg/L)	RR (%)
	3	11.20	2.10	81.25	18.00	3.33	81.48	15.30	2.70	82.35
	6	14.87	2.97	80.04	17.27	3.33	80.70	15.97	2.73	82.88
	9	16.34	3.39	79.23	17.92	3.50	80.47	16.82	3.24	80.72

comparison of the three examples in Table 1 shows that the best removal rate of COD, TN, NH_4^+-N and TP in wastewater is 90.22%, 82.07%, 91.60% and 82.88%, respectively. COD and NH_4^+-N have the best removal rates.

Removal Mechanism Analysis

Contact oxidation pond, biological stabilization pond and submerged culvert oxygen pond adopt different principles to remove pollutants. Contact oxidation pond mainly relies on oxidation to oxidize and degrade pollutants. However, the modified loofah complex was added into the contact oxidation pond of the experimental species, which provided a carrier for microbial film hanging and a reaction carbon source for denitrification decarbonization. In addition, the modified loofah is also an adsorption material. Combined with the degradation and adsorption of microorganisms, it can effectively improve the removal efficiency [23-24]. Compared with ordinary biological stabilization pond, the removal effect is greatly increased, and the seasonal problem of plants is overcome. By planting aquatic plants, aquaculture can be carried out to form a new ecosystem and promote the transfer of energy and the degradation of organic pollutants in wastewater. Submerged plants are planted in the submerged oxygen pond, which can use the photosynthesis and respiration of submerged plants to build an ecological food chain system and realize the deep purification of water quality. Pebbles are preferably paved in the multi-stage falling water oxygenation ecological ditch, and they lay in a single ecological ditch facilitate the propagation and growth of biofilm on pebbles and promote the occurrence of nitrification reaction [25-27]. Aquatic plants are planted at the junction of the two ecological ditches and where the water flow is slow to form a multi-functional water drop oxygenation and ecological ditch, strengthen the purification effect, beautify the environment and increase economic benefits. The traditional ecological ditch follows the law of oxygen vertical curve along the water flow direction, while the multi-stage falling water oxygenation ecological ditch in the experiment is a nondynamic aeration system [28-29]. This can realize the supply of dissolved oxygen in different downstream canal sections without the help of water flow power, contribute to the removal of pollutants, enhance the growth and metabolism of canal plants, and strengthen the interception of N and P removal and infiltration, At the same time, it can greatly reduce energy consumption.

Changes in plant growth over the seasons affect the efficiency and rate of pollutant treatment, and this is unavoidable for any constructed wetland. Different ponds can be selected and combined to achieve the disposal of pollutants by different mechanisms in this paper. Therefore, by choosing the proper ponds in different seasons, a high pollutant treatment efficiency under different seasons can be achieved. The clogging or decomposition of the modified loaf and the death of plants is a problem that most of constructed wetlands need to face. For the system proposed in this paper, the different ponds can be selected and combined depending on the time and pollutant composition. Each pond can also be replaced and cleaned, which can solve the potential clogging problems.

Conclusions

A wastewater treatment system by modular coupling was proposed in this paper. By compared with three examples under different conditions, the conclusions are show as follows:

(1) All examples have excellent treatment effects on wastewater, and the removal rates are about 80%. Compared with example 1 and 3, example 2 has the highest pollutant removal rate due to its long distance.

(2) The system is not sensitive to flow rate, which means it can be used under different hydraulic conditions. After 28 days, the treatment capacity of the system decreased by about 10%, which indicates that the system has good long-term treatment performance.

(3) The system removes pollutants through adsorption of modified loofah complex, oxidation, plant absorption and bacterial nitrification and carbonization. The ponds of proposed wastewater treatment system can be replaced and combined according to the pollutant composition, climate and actual operation status of equipment.

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Conflict of Interest

The authors declare that they have no competing interests.

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