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Eco-symbiotic system constructed and purified effect for wastewater treatment

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Abstract. In order to reduce and deal with domestic sewage from the source, Eco-Symbiotic system (ESS) was built to investigate the biological symbiosis, output of biological organisms and purification of sewage under natural condition. The results showed that the ESS provided good growth for biological symbiosis. Three generation larvae were bred by three guppy couples, and water spinach were harvested 6 times with a total of 4304g in the test period. The ESS has strong buffering capacity, for the stable pH value (7.35-7.75), and the high removal rate of total phosphorus (TP, 89.2%) and total nitrogen (TN, 71.3%). The effluent can reach A level of Urban Sewage Treatment Plant Pollutant Discharge Standards (GB18918-2002). The ESS is a type of treatment to reduce sewage emissions from where the pollution started, improving the utilization of water resources, so it has broader application prospects.

1. Introduction

In order to find a way to solve the increasing discharge of sewage in China, the researchers have focused on how to reduce the discharge of sewage from where it starts, and reducing the burden of the municipal sewage treatment facility.

Ecological symbiosis and microcirculation were the two vital internal mechanisms of efficient utilization the resource and energy from the nature. Constructed wetland technology has been implemented in various fields, such as treatment of sewage from septic tanks, farms, paper mills, oil fields, coal mines, eutrophic lakes, urban life, etc. [1]. It was a technology that made full utilization of plants, microorganisms and the physic-chemical characteristics inside the substrates, through ways of filtration, adsorption, ion exchange, plant absorption and microbial decomposition or other mechanisms [2]. Living Machine system constructed by John Todd's research team, was one of the typical representatives in the artificial ecological intensive treatment of multi-species and multi-stage [3]. Ancient Chinese constructed the mulberry fish pond by digging deep fish pond, raising up the ridge bed, mulberry planting on the ridge and fishing in the pond. It was a rudiment of efficient symbiotic ecosystem [4]. Therefore, with the rapid growth of modern agriculture, a Fish-Vegetable symbiosis system has been put forward by combining the two concepts, aquaculture and hydroponics. It could realize the symbiotic effect with no water charge in aquaculture nor fertilizer applied to hydroponics [5]. However, there were lack of the reports and researches on this technology. Facing the challenges of increasing discharge of sewage, insufficient ability of municipal wastewater treatment, and the lack of public participation, it is vital to construct an efficient symbiosis system. The system is an effective way on purification of sewage from source, of reusing the nitrogen and phosphorus in the wastewater, and promoting the public's participation. Besides, the water can be used efficiently and the related problems can also be solved by the system.

In the research, an integrated Eco-Symbiotic System was designed based on mechanisms of biological symbiosis, biodiversity and food chain. The system has been studied on the purification effect of the main pollutants in the sewage, the outlet of the plant and microorganisms. It provided a feasible way of wastewater treatment for the public.

2. Materials and methods

2.1. Construction of eco-symbiotic system

The ESS (Figure 1) consists of four components (A, B, C, D), each displayed by a dashed line square frame. Part A is Treated water storage unit (SU). Part B is Constructed wetland treatment unit (CWU), which is divided into two parts (B1, B2) by baffle and filled with substrates (large stones, medium (e.g., gravel, crushed stones) and soil). Plants were planted in soil. Part C is an anaerobic decomposition unit for suspended biofilm carriers (ABU). Part D is treated water reflux tank with aquatic animal culture (RTU).

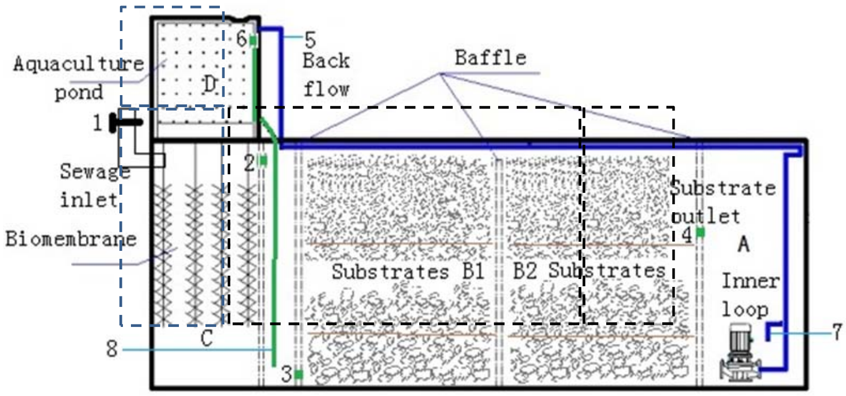


Figure 1. Schematic representation of an eco-symbiotic system (ESS)
Blue line: water-circulating pipe, Green line: Overflow pipe.

1. Sewage inlet, 2.Sewage outlet of ABU, 3. Inlet of CWU, 4.Out let of CWU, 5. Back flow tube 6. Overflow tube, 7.Internal circulation tube, 8.Outlet of overflow.

The sewage flows into the system through the sewage inlet into ABU primary treatment. Effluent after primary treatment flows from Sewage outlet of ABU to Inlet of CWU. After secondary treatment by constructed wetland, treated water flows out from out let of CWU enter Treated water storage unit (SU). Clean water back flow to RTU and inner loop to A by water pump.

2.2. Test conditions

In order to make full use of indoor balcony space for the families, the Eco-Symbiosis system (ESS) was built. The system was 1.2 meters long, 0.3 meters wide, and 0.8 meters high, made of organic glass. The substrate and biofilm were prepared according to the paper [6]. Under natural condition, debugging test of the system was conducted in May 10 2014, and it has been 4 years since it started in May 24 2014. In this paper, the study was on the purification effect of the sewage, and the growth of the plant and microorganisms during the period from May 24 to October 31 in 2014.

Test sewage was mixed wastewater from septic effluent tank and dining hall. The main indexes of the sewage quality were shown in Table 1. Sewage with a total of 4-5 liters was poured into the system once every two days. The submersible pump in the system worked for an hour every two hours, which was adjusted by the timer to control the back-flow to the wetland and the inner recycle in the fresh water tank. The back-flow water yield ratio of the wetland to the inner recycle in the tank was 1:4.

Ipomea aquatica and *Iris pseudacorus* were planted in the purification zone of the wetland system, while six *Poecilia reticulata* and some water weed were grown in the aquaculture box for aquatic animals to graze.

2.3. Methods of water quality measurement

According to the growth situation of the plant, water quality was tested from 9 am to 10 am at the day of plant harvesting. The samples were took from the original sewage, influent of wetland (point 4) and the aquaculture box for aquatic animals (6). To keep the water balance, the supplementary sewage was added for the diminished of testing, while the tap water for evaporation. The physical and chemical indicators were analyzed, such as TP, TN, COD_{Mn}, turbidity, pH, temperature, according to the Standard Method in Water and Exhausted Water Monitoring Analysis method (The 4th edition). The average and standard deviation statistical values of domestic sewage were shown in Table 1 as follows.

Table 1. Averages and standard deviation statistical values of domestic sewage.

Index	Min	Max	Mean	St.D
COD_{Mn}(mg/L)	8.48	109.03	32.92	21.53
Turbidity(NTU)	20.73	109.00	38.54	26.24
pH	6.98	8.39	7.8	0.65
Temperature(°C)	4.10	27.90	17.35	7.01
DO(mg/L)	0.04	7.09	2.24	2.06
TP(mg/L)	0.81	11.01	4.72	2.95
NH_3-N(mg/L)	5.23	56.40	26.03	12.72

3. Results and analysis

3.1. Symbiotic growth of organisms

Table 2. Biological symbiosis growth statistics.

Date	Harvesting wet weight of the plant(g)	Numbers of the fish	Content
May 24	0	6	Plant 12 stems *Ipomea aquatica* rootless, six *Poecilia reticulata* (3 pairs)
June 24	100	8	The first time of *Ipomea aquatica* having , breeding 2 increasing fish
July 6	110	12	The second time of *Ipomea aquatica* having, breeding 4 increasing fish
July 20	144	14	The third time of *Ipomea aquatica* having, breeding 8 increasing fish, some other newborn fish die with back-flow to the filtration system
August 31	1200	20	The fourth time of *Ipomea aquatica* having, breeding14 increasing fish, and 8 fish were transferred to other place to feed, some other newborn fish die with back-flow to the filtration system
September 21	750	12	The fifth time of *Ipomea aquatica* having, fish remained the quantity last time
October 31	2000	10	The sixth time of *Ipomea aquatica* having, 2 accidental fish deaths

The plants and animals grew well from May 24 to October 30 in 2014. 4304g plants were harvested in six times, while 14 larvae of three generation were bred. The biological growth statistics are shown in Table 2. All the nutrient elements needed for biological growth are obtained through sewage purification process, and there was no fertilization or feeding. The plants' growth status in the harvest time were shown in Figure 2 (June 27) and Figure 3 (August 30). Growth status of mother-generation guppy and reproduction of the second batch of small guppy were shown in Figure 4.

Figure 2. Plant growth statue in June 27.

Figure 3. Plant growth statue in August 30.

Figure 4. The growth status of mother-generation guppy and reproduction of the second batch of small guppy.

The large circle for the mother-generation guppy, the small circle for the second-generation guppy

3.2. Buffering capacity

Water temperature and pH are important two factors affecting biological growth and bioactivity. High temperature, strong microbial vitality, strong metabolism, strong oxidation and respiration, better treatment effect [7] [8]. The pH effect significant on microbial nitrification and denitrification [9] [10], dissolved oxygen and primary productivity on purification has significant impact [11]. Therefore, the two indicators are clearly defined in Urban Sewage Treatment Plant Pollutant Discharge Standards (GB18918-2002). The larger the buffer capacity of the system is, the more stable the effluent water temperature and pH value were.

3.2.1. Water temperature. The variation of water temperature in the inflow and outflow of the test period were shown in Figure 5. It could indicate the water temperature varies with the seasons. From May to August, the water temperature showed a rising trend from 24.3℃ to 27.4℃, and dropped to 23.7℃ in September. The water temperature in October was lower than 20 degrees, and dropped to the lowest 18.6℃. The temperature of the effluent after the purification had the same trend as the influent, while the outlet water temperature increased slightly compared with the influent. The microorganisms were mainly anaerobic and facultative microorganisms, both in the sections of precipitation and anaerobic decomposition zone in the former and constructed wetland purification zone in the middle. Heat was produced during the degradation of organic matter and microbial catabolism in sewage, which might be the main reason for average 0.4 degrees higher for the effluent water than the influent.

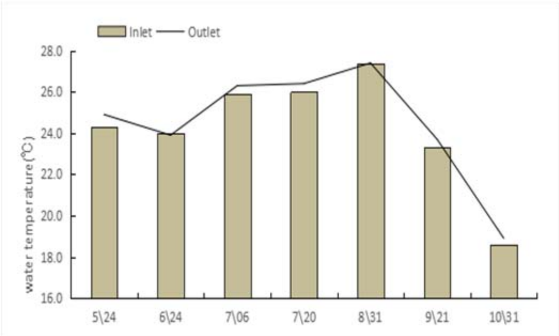


Figure 5. Variation of water temperature during the test period.

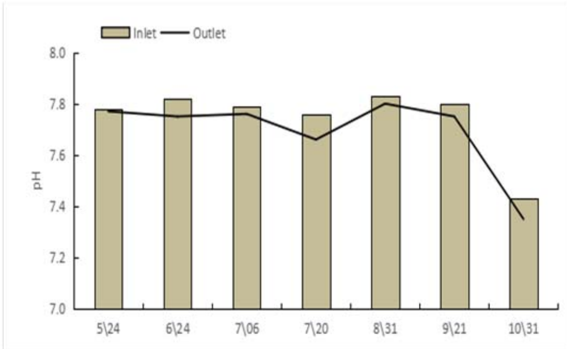


Figure 6. Variation of pH value during the test period.

3.2.2. pH vaule. The variation of pH value in the inflow and outflow of the test period was shown in Figure 6. It could be seen from the figure 6 that the treated sewage was stable in weak alkaline (pH value ranged from 7.43 to 7.82) during the test period and the effluent after purification had the same trend as the influent. Although stained in weak alkaline, the pH value of the effluent with a range from 7.35 to 7.75, was lower than the influent. According to the same logic as is described in 3.2.1, CO_2 was produced during the degradation of organic matter and the microbial catabolism in sewage, and it might be the main reason why the effluent pH was 0.07 lower than the influent.

3.3. Nutrient purification effect.

3.3.1. Total phosphorus. The variation of total phosphorus was shown in Figure 7, while removal rate of total phosphorus during the test period was shown in Figure 8. Phosphorus in wastewater can be removed by adding Ca^{2+}, Al^{3+} or Fe^{3+} to form metal phosphate precipitation, or storing in microorganisms in the form of intracellular phosphorus through the physiological need of microbial growth. The average concentration of total phosphorus of influent reached 5.25mg/L, and the data fluctuated from 3.11 to 6.57mg/L. After treatment, total phosphorus has been effectively purified, with the average removal rate of 89.2% and 95.2% the highest. Water quality was stable that met 1B Standard (TP<1.5mg/L) of the Urban Sewage Treatment Plant Pollutant Discharge Standards (GB18918-2002). After operating for two months, the system has come into the stable period since August 31. The effluent water quality was up to the 1A standard (TP<1.0mg/L), and to the V water quality standard (TP<0.4mg/L) of surface water environmental quality in China (GB3838-2002).

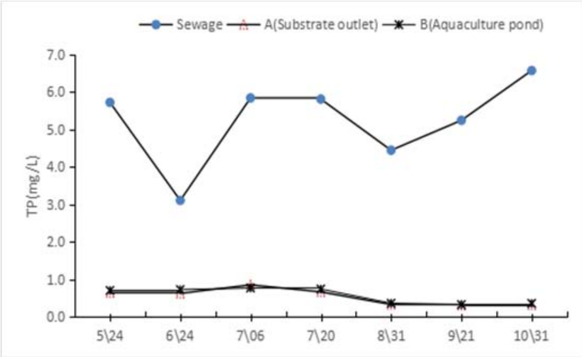


Figure 7. Variation of total phosphorus during the test period.

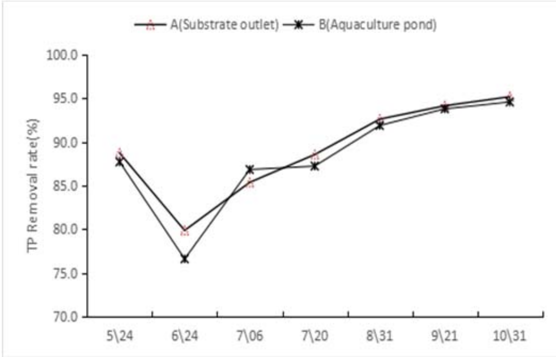
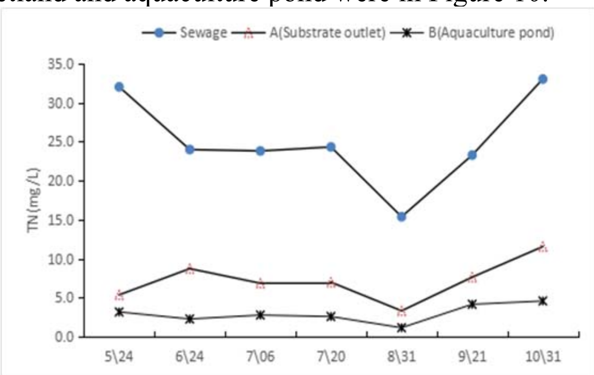


Figure 8. Removal rate of total phosphorus during the test period.

There were two mechanisms of phosphorus removal in precipitation and anaerobic decomposition zone. One was retention, sedimentation, adsorption and filtration of the biofilm. The other was the polyphosphate bacteria accumulating excess phosphorus and energy under anaerobic conditions. Structurally, polyphosphate is a linear polymer formed by hundreds of phosphate monomers (Pi) linked with high energy phosphoric anhydride [12], which acts as phosphorus storage and energy storage.

Low molecular polyphosphate in polyphosphate bacteria stored the phosphorus under anaerobic conditions. For example, low molecular volatile fatty acids were absorbed for storage in the form of polyhydroxyalkanoates (Polyhydroxyalkanoates, PHAs), while polymer polyphosphate for cell growth [13].There were also two mechanisms of phosphorus removal in constructed wetland purification zone. On one hand, a complex with calcium, magnesium and other metal ions in the substrate of the system was formed, then the filtration, adsorption, ion exchange from substrate and plant roots, at last, the absorption by the plant growth. On the other hand, anaerobic and facultative conditions existed simultaneously at different substrate depths. Due to the existence of electron acceptor O_2, the polyphosphate, such as PHAs, in polyphosphate bacteria, can be used as energy and carbon sources in the anaerobic condition for ATP's formation through oxidative phosphorylation for aerobic growth of the polyphosphate bacteria and polyphosphate synthesis, etc. [14]. This might be the reason why the removal of phosphorus in the sewage was further improved by the system after two months' stable running.

3.3.2. Total nitrogen. The variation of total nitrogen of sewage, outflow from wetland and aquaculture pond, were shown in Figure 9, while the variation of removal rate of total nitrogen in outflow from wetland and aquaculture pond were in Figure 10.



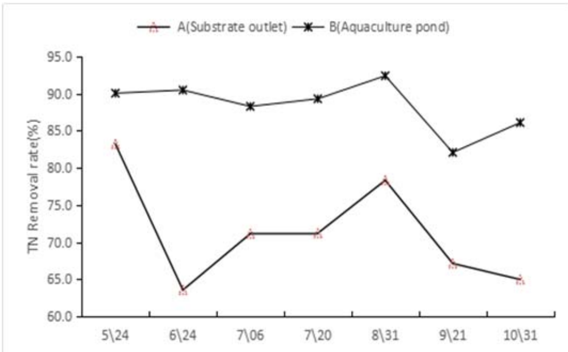


Figure 9. Variation of total nitrogen during the test period.

Figure 10. Removal rate of total nitrogen during the test period.

As the results showed in the Figure 9 and Figure 10, the average concentration of total nitrogen in sewage was 25.1mg/L and fluctuated in the range of 15.4-33.5mg/L. After the treatment through the system, the total nitrogen has been purified effectively in outflow from the wetland and aquaculture pond. The average total nitrogen in effluent from the wetland and aquaculture pond was 7.21mg/L and 2.97mg/L, respectively, and the removal rate was 71.3% and 88.4%. The highest removal rate of total nitrogen from aquaculture pond was 92.4%. The outflow quality was stable and up to 1A (TN<15mg/L) of the Urban Sewage Treatment Plant Pollutant Discharge Standards (GB18918-2002). Meanwhile, it also met the elevated standard of 10mg/L in municipal wastewater treatment plant of the key controlling areas, as compulsory execution standard for discharge of water pollutants in Minjiang River and Tuojiang River in Sichuan Province (DB51/ 2311—2016) asked. Besides, the total nitrogen from aquaculture pond was 4.24mg/L, lower than the outflow from the wetland.

There are two forms of organic nitrogen and inorganic nitrogen in sewage. Ammonia nitrogen transformed from organic nitrogen was converted to nitrite and nitrate by nitrifying bacteria, and nitrate was converted to nitrogen for removal by denitrifying bacteria at last. Meanwhile, biological assimilation can transform nitrogen into cell protoplasm. Sedimentation, biofilm adsorption and filtration in precipitation and anaerobic decomposition zone played a limited part in nitrogen removal, while the constructed wetland purification zone played the key role.

Nitrogen removal by constructed wetland mainly depends on ammonia volatilization, plant absorption, substrate adsorption and precipitation, microbial decomposition and so on. Inorganic nitrogen in sewage was the essential nutrient for plant growth, it was converted to the organic nitrogen by synthesis of plant protein, finally was removed by plant harvesting. Ammonia ions ammonification from organic nitrogen was adsorbed by negatively charged substrate particles, and was converted to NO_3^- by nitrification of various microorganisms in substrate or plant roots. Back-flow recycle system of timing running not only improved the volatilization of ammonia, but also enhanced the effect of denitrifying bacteria, thus further improved the removal efficiency of total nitrogen in aquaculture ponds.

4. Conclusions

The constructed eco-symbiotic system is a semi-open and semi-closed ecological system. When the recirculation ratio of back-flow and fresh water was 1: 4 intermittently under natural condition, the tested organisms can coexist well and intermittently formed a good internal circulation in the system. Besides, the system has an obvious effect on the treatment of nitrogen and phosphorus in sewage, as the average removal rates of total phosphorus and nitrogen were 89.2% and 71.3%, respectively. The total phosphorus and total nitrogen of effluent can reach the 1 A discharge standard of pollutant discharge standard (GB18918-2002) of municipal wastewater treatment plant. The system has the advantages of simple operation, low cost of maintenance and operation. It can also grow grass and fish in the process of sewage treatment, increase income, save resources, and get better economic and ecological benefits. The ESS can be used in an ordinary family. It is a facility which can treat and reduce the discharge of domestic sewage from the source, improving the use efficiency of water resources, with a broader application prospect.

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