The Influence of Nutrient Removal by Different Harvest Time of the Emerged Plant in the Wetland System

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Abstract. In order to avoid the secondary pollution caused by the withering of plants, experiments on reasonable harvesting time of emerged plants in the constructed wetland (CWs) was conducted. The results showed that the best plant regrowth and nutrients removal efficiency by harvested plant were happened when plants were harvested at the withering period (January). Whenever plants were harvested, the removal amount of nitrogen and phosphorus in the CWs was greater than that in the non-harvesting CWs. When plants were harvested at the early growing period, the removal of nitrogen and phosphorus by the CWs reached the maximum, which were 92.39 mg·L⁻¹ and 237.17 mg·L⁻¹, respectively. Therefore, based on the plant regrowth and nutrient removal efficiency of the CWs, it is suggested to harvest emerged plants after the growth period (preferably the withering period), which will be most conducive to the long-term effective operation of the CWs.

Keywords: Harvest time, Constructed wetland, Nutrient remove, Emerged plant

1. Introduction

In recent years, constructed wetlands (CWs) is considered as a new ecological restoration technology with low cost, good economic benefit and obvious landscape benefit. As an important part of CWs, plants can absorb pollutants in the water and convert them into nutrients needed for their own growth through photosynthesis [1]. The researches on wetland plants mainly focused on the selection, configuration and purification capacity of different plant species [2-4], lacking comparative analysis on plant harvest management.

It is generally believed that harvesting wetland plants can avoid the secondary pollution caused by their decay and improve the removal rate of nitrogen and phosphorus [5]. The jury is still out on whether harvesting should be done and when best to do it. Studies had shown that the selection of harvest time should be related to the growth of plants [2,6]. After harvesting at the appropriate time (last August and February to March), the secondary germination of plants can be effectively promoted, so that the plants can grow again after harvest and the absorption time of contaminated nutrients can be prolonged [2,7]. Other researches believed that only when plants are mature or harvested in autumn and winter can the eutrophication degree of water be reduced to the maximum extent. However, according to study of Wang et al. [6], when harvesting plants at the end of autumn, it was not conducive to the oxygen-producing effect of the root system, thus affecting the microbial quantity and activity of the CWs in winter and reducing the removal capacity of pollutants. It was recommended to harvest the plants when the temperature drops below 4 °C. At the same time, harvest time varied due to different plant types [8].
The effluent quality of CWs was affected by the harvest time, harvest intensity, harvest frequency and so on. Under the warm climate with low pollutant concentration condition in the CWs, plant harvesting can reduce concentration of SS and COD in effluent [9]. And in the cold areas, the removal efficiency of pollutants was not significantly affected by plant harvesting [10]. Under certain hydraulic loading, the increase of plant harvesting frequency will reduce the removal amount of nitrogen and phosphorus, but not affect the removal of COD [5]. Resuspension of the substrate after harvest and changes in the organisms attached to the plant may affect the aquatic environment.

This study will focus on chosen of suitable harvest time of the wetlands plant. A mixed emerged plants CWs system, concluding Thalia dealbata, Phragmites communis, Iris wilsonii, Acorus tatarinowii and Phyllostachys heteroclada, is using for study the sewage purification effect of wetland at different harvesting time. The result will provide scientific basis and data to management and maintenance of constructed wetlands.

2. Materials and Methods

2.1. Experimental Setting

The experiment was carried out in the CWs simulator under the awning of the Purple Soil Agricultural Ecology Experimental Station, CAS, in Yanting, Sichuan Province. The experiment started from July 16, 2018 and ended on April 16, 2019, with a total CWs operation period of 9 months. The CWs simulator is a PVC plastic bucket with a diameter of 40cm and a height of 50 cm, with water flowing from the upper part and water flowing out in the lower part. The total thickness of the wetland matrix layer was 28 cm and the overlying water depth in the simulator was 10 cm. Mixed emerged plant samples were selected from the ecological ditch in Yanting. Selected plants with normal growth and basically the same size, was transplanted into simulator to domesticate for 1 to 2 weeks, and then start the harvest experiment when the CWs was stable. The planting density of each plant was as follows: 16·m$^{-2}$ of Thalia dealbata, 24·m$^{-2}$ of Iris wilsonii, 40·m$^{-2}$ of Phragmites communis, 32·m$^{-2}$ of Acorus tatarinowii, 24·m$^{-2}$ of Phyllostachys heteroclada.

2.2. Harvest Time Setting

Experiments were carried out to simulate the influence of mixed plants harvested at different times during the CWs operation. The harvest method was above-ground partial harvested (about 10cm above ground plant stems were kept). The harvest time was listed in table 1, representing the five typical vegetative stage of CWs, defined as early growth period, exuberant growth period, growth period, withering period and dormancy period. The influent and effluent water quality and plant growth in the CWs were monitored from July 16, 2018 to April 16, 2019. Three parallel CWs samples and a blank control with no plants were assigned to each group. The water change time of the CWs was set as 7 d.

| Represent | Initial time | Harvest time | Finished time | The period of plant growth |
|-----------|--------------|--------------|--------------|---------------------------|
| HT1       | 2018.7.16    | 2018.8.16    | 2019.4.16    | Early growth period       |
| HT2       | 2018.7.16    | 2018.9.16    | 2019.4.16    | Exuberant growth period   |
| HT3       | 2018.7.16    | 2018.11.16   | 2019.4.16    | Growth period             |
| HT4       | 2018.7.16    | 2019.1.16    | 2019.4.16    | Withering period          |
| HT5       | 2018.7.16    | 2019.3.16    | 2019.4.16    | Dormancy period           |
| NHT       | 2018.7.16    | --           | 2019.4.16    | --                        |
2.3. Sample Collection and Analysis

2.3.1. Water Samples. Each 7 to 14 d water samples in influent and effluent of CWs was collected to analyze physical and chemical index. Among them, water temperature, pH and DO was measured in-situ using portable instrument, and concentration of TN and TP were measured using AA3 flow analyzer. All data analysis methods were based on “Water and Wastewater Monitoring and Analysis Method”.

2.3.2. Plant Samples. Mixed plant samples (stems and leaves or roots) were collected at the beginning of the experiment, at the harvest time and at the end of the experiment. After washed by tap water and deionized water, plant was dried to constant weight at 65 °C, and then measured the biomass. The dried samples were cut into 1-3 cm segments and then ground through 60 mesh sieve to measure the nitrogen and phosphorus nutrient contents. After digestion with H2SO4-H2O2, the content of total nitrogen was determined by Kjeldahl distiller, and the total phosphorus was measured by Mo-Sb-Vc.

2.4. Data Calculation and Statistics

The nutrient absorption by wetland plants (stems and leaves or roots) during the operation of the CWs was calculated according to the variation of dry weight nutrient content of plants. The absorption amount of nitrogen and phosphorus by plant was calculated as follows:

\[
T_1 = N_i \times W_i - N_0 \times W_0
\]
\[
T_2 = N_t \times W_t
\]
\[
T_3 = N_i \times W_t - N_0 \times W_0
\]
\[
T = T_1 + T_2 + T_3
\]

Where, \(T\) was the absorption amount of nitrogen and phosphorus content by plant per square meter (g·m⁻²), \(T_1\) was the cumulated amount of nitrogen and phosphorus content by plant stems and leaves (g·m⁻²), \(T_2\) was the uptake amount of nitrogen and phosphorus content by plant regenerated stems and leaves after harvest (g·m⁻²), \(T_3\) was the amount of nitrogen and phosphorus content by plant roots during the whole experiment (g·m⁻²). \(N_0, N_i, N_t\) were the plant (stems and leaves or roots) nutrient content at the initial time, harvest time and the end, respectively (g·g⁻¹). \(W_0, W_i, W_t\) were the dry weight of plant (stems and leaves or roots) at the initial time, harvest time and the end (g·m⁻²), respectively.

The variation of water quality during the wetland operation process was expressed by the removal rate and amount of TN and TP. The specific calculation formula was as follows:

\[
\text{Removal rate} = \frac{C_{in} - C_{out}}{C_{in}} \times 100\%
\]
\[
m_i = (C_{in} - C_{out}) \times V_i
\]
\[
M = \sum m_i
\]

Where, \(C_{in}\) was the concentration of TN and TP in the influent water for a certain period (mg·L⁻¹), \(C_{out}\) was the concentration of TN and TP in the effluent water for a certain period (mg·L⁻¹), \(m_i\) was the amount of TN and TP removed in a certain period (mg⁻¹), \(V_i\) was the overlying water volume for a hydraulic retention time (L) and \(M\) was for the nutrient remove amount of the CWs (mg⁻¹).

Excel and SPSS were used for statistical analysis of the data. All graphs in this paper were drawn by Origin 6.0.

3. Result

3.1. Plant Regrowth after Harvest
Table 2 listed the biomass at different harvesting time. It can be seen that the maximum biomass of stems and leaves was 1711.66 g·m⁻², by harvesting at HT2, which was consistent with the observed plant grow. However, the regeneration biomass of stems and leaves and roots were relatively small at that time, 66.24 g·m⁻² and 37.66 g·m⁻², respectively. Then, as the plant continue to grow in the CWs with temperature decreased, the stem and leaves biomass began to decline, while the root biomass increased. At HT4, *Iris wilsonii* gradually died, and the other plant species in the CWs became yellow and withered, leading to the decline of biomass. And the plant biomass of regrown after harvest reached the maximum to 664.49 g·m⁻² (stems and leaves) and 680.57 g·m⁻² (roots). When the plant was in dormancy (HT5), the root of these perennial plant continued to grow, and started to sprout with the temperature rise. As a result, the amount of biomass of stems and leaves increased to 297.61 g·m⁻² after plant harvested at HT5.

| Harvest time | At the beginning | When harvest | In the end |
|--------------|-----------------|--------------|------------|
|              | Stems and leaves | Roots        | Stems and leaves | Stems and leaves | Roots |
| HT1          | 383.97          | 454.38       | 657.36      | 116.40         | 488.54 |
| HT2          | 383.97          | 454.38       | 1711.66     | 66.24          | 37.66  |
| HT3          | 383.97          | 454.38       | 1355.33     | 553.34         | 200.24 |
| HT4          | 383.97          | 454.38       | 899.44      | 664.49         | 680.57 |
| HT5          | 383.97          | 454.38       | 856.73      | 297.61         | 393.15 |
| NHT          | 383.97          | 454.38       | --          | 767.95         | 290.53 |

### 3.2. Nutrients Uptake by Plant

Figure 1 showed the amount of N and P absorbed by plant at different harvest time during the whole experiment. It showed that the uptake effect of N and P by plant in the CWs were similar at different harvest time. At HT1, a large number of N and P can be taken away by harvesting plant stems and leaves. At this time, the plant root was not well developed, which made that the amount of nutrients absorbed by stems and leaves of regrow plant after harvest was small. At HT2, plant grew rapidly to absorb a large amount of N and P for its growth, resulting in lots of pollutants removed by plant harvesting. Little stems and leaves could regrow after harvest, and the nutrients absorbed by the root initially could not be taken away at the end of the experiment. At HT3, the N and P content that can be taken away by stems and leaves and roots by plant harvesting was lower than that at HT2. However, the re-germination and growth of plants at HT3 were motivated by harvest, thus absorbing more N and P from the CWs.

![Figure 1. The amount of N and P absorbed by emergent plant during the whole experiment.](image-url)
As temperature dropped in the winter, plant began to wither, making it easier for plants to absorb and utilize less of the nutrients in the CWs at HT4. However, the survival of root at HT4 promoted the regeneration of stems and leaves after harvest, so that the CWs showed a better effect of nutrients removal at that time. When harvesting at HT5 after withering and rotting, the stems and leaves absorbed little nutrients from CWs and the pollutants were mainly consumed by root uptake. And the plant would sprout and grow after harvesting and running for another month. From August to next April, the stems and leaves accumulated a small amount of nitrogen and phosphorus at NHT (1.87 g N·m⁻² and 0.23 g P·m⁻²), but the roots released nitrogen and phosphorus of 0.30 g N·m⁻² and 0.43 g P·m⁻². Overall, plants absorbed nitrogen and released phosphorus during the whole experiment.

In general, above-ground harvesting of plants at HT3 and HT4 were more conducive to nutrient removal in the CWs, and also considering the landscape effect.

### 3.3. Variation of Effluent Quality

The water temperature, pH and DO of effluent in the CWs during the whole experiment at different harvest time were exhibited in figure 2. It can be seen that whether harvesting or not had little influence on the overlying water temperature of CWs. After harvest at HT2, the temperature of overlying water showed larger fluctuation than that at HT1 and HT3, but there was no significant difference compared with that at NHT. When harvesting plants at different time, the difference between effluent pH and influent pH was not very obvious. However, the DO concentration in the effluent at all of the harvesting time was slightly higher than that in the inlet, due to the grow of plants increased the DO concentration and enhanced the aerobic degradation of organic matter to a certain extent.

![Figure 2. The effluent water temperature, pH and DO concentration during the whole experiment.](image-url)

The average TN and TP concentrations in the influent of the CWs were 7.23 mg·L⁻¹ and 13.78 mg·L⁻¹, respectively. And the variation of TN and TP concentrations in the effluent at different harvest time during the whole operation were shown in figure 3. The TN concentration in the effluent of the CWs gradually decreased with the time of harvest, and the average effluent TN concentration at HT1, HT2, HT3, HT4 and HT5 was 1.80, 1.34, 1.20, 1.13 and 1.38 mg·L⁻¹, respectively, which were slightly lower than that at NHT (1.62 mg·L⁻¹). The average TP concentration in the effluent of the CWs at HT1, HT2, HT3, HT4, HT5 and NHT was 5.09, 5.96, 6.74, 7.27, 11.87 and 6.23 mg·L⁻¹, respectively. It can be demonstrated that the time of harvest had a great influence on the TP concentration in the effluent of the CWs.
3.4. Nutrient Removal Efficiency

The average nutrient removal rate of the CWs was compared within 28 days after harvesting and during the whole experiment (including the CWs operation before harvesting and following operation after harvesting), as shown in Table 3. During the whole experiment, the removal rate of TN in the CWs was less affected by plant harvest. However, the removal rate of TN at HT3 after harvesting and continue to run for 28 days was the maximum, for 86.76%. The removal rates of TP after harvest during the whole operation of the CWs decreased with the delay of harvest time and were higher than that at NHT. However, the removal rates of TP after harvest within 28 days were significantly lower than that at NHT, especially for that at HT5.

### Table 3. Removal rate of pollutions from CWs at different harvest time / %.

| Harvest time | TN(during the whole experiment) | TN(within 28d after harvesting) | TP(during the whole experiment) | TP(within 28d after harvesting) |
|--------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| NHT          | 67.59                           | 59.48                           | 51.72                           | 74.85                           |
| HT1          | 66.47                           | 65.49                           | 62.48                           | 72.35                           |
| HT2          | 66.57                           | 71.49                           | 61.30                           | 44.10                           |
| HT3          | 68.56                           | 86.76                           | 55.81                           | 60.58                           |
| HT4          | 68.23                           | 74.87                           | 53.82                           | 58.19                           |
| HT5          | 67.02                           | 53.37                           | 51.83                           | 27.20                           |

Figure 4 showed the cumulative removal amount of TN and TP in the water by the CWs at different harvest time. In the absence of plant harvesting (at NHT), the cumulative removal amount of TN and TP in the water from the CWs were 86.25 mg·L$^{-1}$ and 183.89 mg·L$^{-1}$, respectively. As the time of harvest went on, the cumulative removal amounts of TN and TP in the CWs changed in a same way and gradually decreased. The removal amount of TN and TP from the water during the whole experiment reached the maximum at HT1, which were 92.39 mg·L$^{-1}$ (TN) and 237.17 mg·L$^{-1}$ (TP), respectively.
4. Discussion

4.1. Effect of Harvesting on Regeneration Growth of Emergent Plants

The growth of plants in the CWs is not only affected by natural environmental conditions, such as temperature, humidity and soil conditions, but also restricted by harvest time and frequency [5,8]. Harvesting can provide more space and light conditions for plant regeneration [5]. Suitable harvesting can change the physiological characteristics and growth of plants, and indirectly affect the pollutant removal ability of the CWs by aggrandizing the amount of microorganisms [11]. Harvesting would stimulate the secondary germination and regrowth of plants, and the biomass of plants will increase to different extents according to different plant species [1,7,8]. Generally speaking, plants grew relatively slowly in the first week after harvest, and became grow faster in the second week, and recovered to the level of no harvest within a month.

At HT1, plants (such as Thalia dealbata) regenerated in 1 to 2 weeks after harvesting, but the nutrients amount absorbed by regrowth plants was different from that before harvest. And the growth of plants was slower than that at NHT, due to the metabolism of organic matter in plant root was affected by harvesting, impeding the growth of new plant. In winter, the plants would be withered and died again. After harvest at HT2 and HT3, the nutrients amount absorbed by plants reached the maximum, which were mostly used for plant growth. At HT4, plant had no longer absorbed nutrients and turned yellow with not fully decomposed. When harvesting at that time, nutrients taken by plants were not the most, but the regeneration rate and nutrient absorption rate of plant were very fast. And the relative growth rate returned to same as that at NHT till next spring. Meanwhile, the low air temperature and barely radial oxygen loss of plant root at HT4 might be weaken the microbial action in the CWs [6]. At HT5, plants decayed completely and be unable to regrow, which will release nutrients into the CWs. So after harvesting, the biomass of regrowth plants was less than that before.

4.2. Effect of Harvesting on Pollutant Removal

Harvesting of plants can not only change the DO concentration in water and promote microbial activity, but also damage plant and more nutrients are needed to meet the anabolism of plants to restore the division and differentiation of plant cells, thus affecting the removal of pollutants in the CWs [3,12]. Different from the commonly believed that the CWs without plant harvest performed the best purification effect on sewage [6], the plant harvesting in this study will effectively improve the removal effect of the CWs on nitrogen and phosphorus pollutants [5]. However, early or late harvesting of plants will affect the contaminant removal capacity of the CWs. Early harvesting may lead to little nutrient remove amount because plants have not yet exerted their optimal absorption capacity, while delayed harvesting may cause secondary pollution due to decomposition of plants and re-release of pollutants into the CWs [13].

The enhanced assimilation and absorption of plants after plant harvesting in winter could accelerate plant regeneration to improve the TN removal efficiency of the CWs [2,5]. The removal of TN in the CWs includes physical interception, plant assimilation and absorption, nitrification and denitrification.
of microorganisms, and adsorption of water particles and substrates [14]. In this study, ammonification, nitrification and denitrification, which caused by plant absorption and microbial action, significantly reduced the inorganic components containing nitrogen in the effluent of the CWs. At the same time, withered plant in low temperature led to the increase of organic nitrogen content in the water. However, regular harvesting of plants caused the variation of DO content and indirectly changed the number and activity of microorganisms in the CWs, thus boosting the nitrification and denitrification capacity of the CWs [15]. The removal of TN by the CWs in the long term was not affected by plant harvesting, but in the short term after harvesting, especially harvesting in winter (From November to January), the TN removal efficiency will be improved and the re-growth and germination of plants can be promoted in spring. Because after plant harvesting, plants relied on the nutrients stored in the root and part of the residual stem to supply the germination and growth of new branches and leaves. At the same time, the decrease of the oxygen-secreting rate of root after harvesting affected the normal metabolism of organic matter in the root, and the demand for oxygen and nitrogen was relatively low [6]. The removal of phosphorus in the CWs is mainly affected by root interception, plant assimilation and absorption, and negligible microbial action [15,16]. Researches have shown that plant harvesting contributed up to 22.5~59.5% of TP removal efficiency in the CWs, but its effect lagged behind substrate adsorption and precipitation [17]. After harvesting at HT1, the plant roots had no longer released phosphorus to the CWs, which made the substrate adsorption stronger, leading to the optimal phosphorus removal efficiency of the CWs. As the warm climate at HT2 and HT3, plant harvesting reduced the amount of granular suspended matter (which can absorb phosphorus) in the effluent of the CWs [9,10], but made no difference in the removal of soluble phosphate. However, plant harvesting would weaken the removal of phosphorus in the CWs as the temperatures dropped. This was because that the absorption rate of phosphorus by plants decreased with the decrease of temperature, the assimilative absorption capacity of phosphorus decreased after the decline of plants at HT5, while the decomposition of plants would lead to the re-release of phosphorus in the plant into water [13,18].

5. Conclusion
Plants can regenerate after harvesting at different times, while the regeneration and nutrient absorption of plant achieved the best at HT4 (withering period). The average TN and TP concentrations in the effluent of the CWs were different at different harvesting time. And the minimum TN concentration in the effluent of the CWs was 1.13 mg·L⁻¹ when plant harvested at HT4, while the minimum TP concentration was 5.09 mg·L⁻¹ at HT1. The removal rate of TP in the CWs decreased with the delay of harvesting time. However, the removal of nitrogen and phosphorus in the harvesting CWs was greater than that in the non-harvesting one, regardless of the harvesting time. When harvest at HT1, the removal of TN and TP by the CWs reached the maximum, which were 92.39 mg·L⁻¹ and 237.17 mg·L⁻¹, respectively. Therefore, it is suggested that the aboveground harvesting of emerged plants should be carried out at the growth period (the best period is the withering period), which will not only make the CWs has strong pollutant removal effect, but also promote the plant regrowth and landscape benefits, which is most conducive to the long-term effective operation of the wetland system.

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