Impacts of aquatic macrophytes configuration modes on water quality
Jiakai Liu, Jinglan Liu, Rong Zhang, Yuqi Zou, Huihui Wang and Zhenming Zhang

ABSTRACT

 Constructed wetland technology is regarded as an important ecological restoration technology and used widely in sewage disposal. In order to give them a wider scope of application and to improve their performance in water restoration, the current experiment was designed. Four aquatic macrophytes (dwarf cattail (TM), yellow-flowered iris (WI), water shallot (ST) and watermifoil (MS)) were picked and planted in artificial floating islands (AFIs) in different configurations (TM + WI, ST + MS and TM + WI + MS) and two patterns, radiation pattern (RP) and annular pattern (AP), for a 60-day experiment. Then, water quality and growth were monitored every 10 days. The results indicate that the different configurations performed diversely on waste water purification. First, a composite plant configuration removed more pollutant than a single one with the same total increment of biomass. Second, the plant configuration of MS + ST was most effective in total nitrogen (TN), total phosphorus (TP) or PO₄³⁻ removal, and TM + IW + MS was good at chemical oxygen demand (COD) and NO₃⁻ removal. However, different patterns comprised from the same species had a certain effect on absorption of pollutants. Generally speaking, plant configurations with a RP were better than an AP in purification. Accordingly, these provided the methods for the pollution wetland restoration.

Key words | aquatic macrophytes, configuration mode, water quality, wetland restoration

ABBREVIATIONS

AFIs  artificial floating islands
AP   annular pattern
MS   watermifoil (Myriophyllum spicatum)
RP   radiation pattern
ST   water shallot (Scirpus tabernaemontani)
TM   dwarf cattail (Typha minima)
WI   yellow-flowered iris (Iris wilsonii)

INTRODUCTION

 Constructed wetlands technologies have been used for some time in the domain of water purification and aquatic environment recovery (Healy et al. 2007; Kanagy et al. 2008; Song et al. 2009). The original intention of the technologies was to copy the ecosystem service functions of natural wetland ecosystems in order to resolve ecological problems (Vymazal 2010). However, some defects exist in traditional constructed wetland technologies (surface, horizontal subsurface and vertical constructed wetlands), such as the irreplaceable matrix, limited range of application, and so forth. In order to overcome these shortcomings, artificial floating islands (AFIs) have been used as a matrix in recent studies. Using AFIs to take the place of traditional matrix materials has four major advantages in constructed wetlands: (1) increasing their service life; (2) expanding the range of applications; (3) providing habitats for certain animals, aquatic macrophytes and microorganisms; and (4) the enhancement of landscape features (Nakamura et al. 1999).

Stewart et al. (2008) put Bio-Heaven™ AFIs directly into a tank (without plants on them) as a constructed wetland to provide habitats for bacteria. This study demonstrated that this kind of AFI had excellent potential for use as an alternative to conventional treatment wetlands for reducing excess concentrations of ammonium, nitrate and phosphate.
(Stewart et al. 2008). However, aquatic plants are the key component of wetland ecosystems (Brix 1997; Egerton et al. 2004). They increase the contact time between the water and plants by reducing the velocity of the water, they provide surface area bio-films, take up nutrients and release oxygen (Brix 1997) to form a buffer against the degradation of water quality (Egerton et al. 2004). Therefore, hydrophytes should be used in a mature constructed wetland water treatment technology. Tanner & Headley (2008) designed a floating treatment wetland in Hamilton to take up excess fine suspended particulates in urban stormwater. Four local aquatic species were planted on AFIs, consisting of four different single configuration groups (AFI + Carex virgata, AFI + Cyperus ustulatus, AFI + Juncus edgewae, AFI + Schoenoplectus tabernaemontani) and a control group. Their performances were compared, but the distinction was not significant. The results showed the potential in application of all of them for removal: copper (Cu) removal rates were between 65–75%; Zinc (Zn) removal rates were about 60%; and fine suspended particulate removal rates were between 57–67%. Yao et al. (2011) monitored the capacities of different single plant configurations: (1) softstem bulrush (Scirpus validus), (2) spiked loosestife (Lytthrum salicaria), (3) yellow-flowered iris (Iris wilsonii), (4) dwarf cattail (Typha minima), and a control group (AFI without vegetation) for maintaining and enhancing water quality and ecosystem capital. This study showed that spiked loosestrife (L. salicaria) was the best group in phosphorus removal (93.9% of PO4– and 82.0% of total phosphorous). The AFI with softstem bulrush (S. validus) had the strongest ability to remove nitrogen (96.9% of total nitrogen). Moreover, this experiment proved that AFIs with plants have a significantly greater capacity to purify wastewater than those without plants. This was probably because the plant roots provided the environment needed by microorganisms, and aquatic macrophytes also took up some pollutants in during the growing season.

In this experiment, four species of macrophytes were selected: dwarf cattail (Typha minima), yellow-flowered iris (Iris wilsonii), water shallot (Scirpus tabernaemontani), and watermilfoil (Myriophyllum spicatum). These plants had the following characteristics: (1) they were common species in local nature wetland ecosystems (Lei et al. 2009); (2) they are widely used in constructed wetland and easy to buy; and (3) they are adapted to growing on AFIs (Yao et al. 2011). The plants were collected from Beijing’s parks.

METHODS AND MATERIALS

Experimental materials

In this experiment, four species of macrophytes were selected: dwarf cattail (Typha minima), yellow-flowered iris (Iris wilsonii), water shallot (Scirpus tabernaemontani), and watermilfoil (Myriophyllum spicatum). These plants had the following characteristics: (1) they were common species in local nature wetland ecosystems (Lei et al. 2009); (2) they are widely used in constructed wetland and easy to buy; and (3) they are adapted to growing on AFIs (Yao et al. 2011). The plants were collected from Beijing’s parks.

Experiment design

In this experiment, three kinds of plant configuration and two kinds of patterns were designed (Figure 1). The entire experiment contained 30 cylindrical water jars and each contained five replications (Table 1). The water jars were set up under a clear-plastic shelter. Each water jar had a floor diameter of about 0.60 m with a height of 1.10 m. All AFIs used in these experiments were of the same size, with a length of 0.4 m, a width of 0.38 m and a height of 0.10 m. First, the aquatic macrophytes were placed in the same clean water pretreatment environment for about five days, and subsequently placed in the experiment design. The plant height of each was controlled at 0.30 m. Initial concentrations were measured and recorded as follows: (pH 8.40, chemical oxygen demand (COD) 38.15 mg/L, PO43– P 1.35 mg/L, NO3– N 1.29 mg/L, total nitrogen (TN) 2.75 mg/L, total phosphorus (TP) 0.49 mg/L). In addition, Yao et al. (2011) certified the efficiency of plants in artificial wetland ecosystems, so a control group (AFI without plants) was not set up in this experiment.

Data analysis

Initially, pH, COD, TN, and TP were measured in each water jar. In the experimental period (from 10 June 2012...
to 30 July 2012), the chemical parameters were measured six different times (10, 20, 30 June, and 10, 20, 30 July).

Two-factor analysis of variance (Fisher 1940) was applied to processing data:

$$SS_T = \sum_{i=1}^{a} \sum_{j=1}^{b} (X_{ij} - \bar{X})^2$$

$$SS_A = b \sum_{i=1}^{a} (\bar{X}_i - \bar{X})^2$$

$$SS_B = a \sum_{j=1}^{b} (\bar{X}_j - \bar{X})^2$$

$$SS_E = \sum_{i=1}^{a} \sum_{j=1}^{b} (X_{ij} - \bar{X}_i - \bar{X}_j + \bar{X})^2$$

$$F_A = \frac{SS_A/\alpha}{SS_E/\beta} - F(\alpha, \beta)$$

$$F_B = \frac{SS_B/\beta}{SS_E/\beta} - F(\beta, \beta)$$

where $A$ stands for the configurations as a factor, $B$ stands for the patterns as another factor, $\alpha (=5)$ is the number of configurations, $\beta (=2)$ is the number of patterns, $f_A = (a-1)$, $f_B = (b-1)$, and $f_E = (a-1)(b-1)$ are the degrees of freedom. Then, if $F_A > F(\alpha, \beta)$, the difference was defined as significant on confidence level $\alpha$. In the same way, if $F_B > F(\beta, \beta)$, the difference was defined as significant on confidence level $\beta$. In the current research, plant groups were tested at two different
TABLE 1 | Schematic representation of the experimental design

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AR: dwarf cattail (T. minima) and yellow-flowered iris (I. wilsonii) on AFI with radiation pattern, AP: dwarf cattail (T. minima) and yellow-flowered iris (I. wilsonii) on AFI with annular pattern, BR: watermifoil (M. spicatum) and water shallot (S. tabernaemontani) on AFI with radiation pattern, BP: watermifoil (M. spicatum) and water shallot (S. tabernaemontani) in AFI with annular pattern, CR: dwarf cattail (T. minima), yellow-flowered iris (I. wilsonii) and watermifoil (M. spicatum) on AFI with radiation pattern, and CP: dwarf cattail (T. minima), yellow-flowered iris (I. wilsonii) and watermifoil (M. spicatum) in AFI with annular pattern.

RESULTS AND DISCUSSION

During the study period, the growth status of different aquatic macrophytes varied from group to group. The increase of overground biomass varied at about 6.0 g/m² (Figure 2), but the underground biomass growth of MS and ST (1.25 g/m² on average) was far below that of dwarf cattail TM and WI (6.54 g/m² on average). However, the results were totally different in terms of plant height and root length, and ST grew quickly. Another phenomenon worthy of attention is that aquatic macrophytes in AFI with a radiation pattern increased their biomass (0.92 g/m² on average) more than those with an annular pattern.

The COD displayed clear trends in all the experiment groups (Figure 3). Levels fell dramatically, especially in group C (decreased 26.347 mg/L on average). On the other hand, the plants in a radiation pattern performed better than those in the annular pattern for COD removal in all three groups. Furthermore, standard deviations were lower in plants with the radiation pattern than with the annular pattern (more COD removed: 4.95% in group AR than AP, 13.57% in group BR than BP, and 13.56% in group CR than CP, Table 2).

As for NO₃⁻ removal, the results were similar to the process for COD. First, each group can clearly lower contents of NO₃⁻ in 20 days, especially group BR (from 1.285 to 0.080 mg/L) and CR (from 1.285 to 0.070 mg/L). Second, the same plant disposition in different patterns showed different abilities in removing NO₃⁻, and the radiation pattern had a better effect in all groups. The BR and CR groups are worth further attention because the experiment results were nearly the same; however, group BR used fewer species.

All curves decreased, and different groups had clear effects on removing PO₄³⁻. At the same time, some details merited attention. Groups BR and BP removed a little more PO₄³⁻ (from 1.350 to 0.080 mg/L in annular pattern and from 1.350 to 0.145 mg/L in radiation pattern) than other plant configuration groups with the lowest standard deviations during the experiment period. In addition, the radiation pattern had a better effect than the annular pattern. But it is worth mentioning that the difference in removing PO₄³⁻ was not obvious: more was removed (6.963% on average) in group AR than in AP, 4.815% in group BR than BP, and 8.519% in group CR than CP.

In spite of having the same starting content at 0.485 mg/L, the final results were especially evident. Among these, the ultimate amounts for the six groups were: AR 0.105 mg/L, AP 0.126 mg/L, BR 0.586 mg/L, BP...
was 0.421 mg/L, CR 0.053 mg/L and CP 0.780. Through the data, it can be demonstrated that plants in those AFIs with a radiation pattern had advantages in removing TP content from the water body. Furthermore, dwarf cattail (T. minima) and yellow-flowered iris (I. wilsonii) released phosphorus into the water body in the first 10 days.

On the whole, groups AR and AP did not show the expected effects in removal of TN. By contrasting the curves of groups BR, BP, CR and CP, the comparison of group AR and AP between the beginning (2.750 mg/L) and the end (1.254 mg/L) was not very obvious. Moreover, the same plant configurations with a radiation pattern still showed a greater ability in removing TP than those with an annular pattern.

The pH value reflected a measure of the acidity or alkalinity of a solution. Groups AR and AP show an ascending trend after 20 days, rising from 8.40 to 8.64 and 8.54, respectively. Other groups changed little during the experiment period, and wavered between 8.15 and 8.66, against an initial value of 8.40.

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The purification capacity of vegetation in AFIs has been proven in earlier studies that described the characteristics in plant growth, nutrient removal and the pH changes of different species. However, they rarely focused on plant configuration and patterns. This study indicates that differences exist between arrangements of plants in AFIs on water purification. Variance analysis can help to determine the optimal choice of plants when a constructed wetland is designed and built in order to solve different questions of water treatment or ecosystem restoration.

In Yao et al.’s (2011) experiment, single plant configurations were designed, and species dwarf cattail (T. minima) and watermifoil (M. spicatum) were selected. The total biomass of plants in a single AFI was approximate to the biomass in this study, so these two experiments are comparable. The composite plant configurations had an advantage over the single ones, especially those with the radiation pattern (Table 3). Furthermore, the composite plant configurations were used or studied in many full-scale or pilot-scale studies (Hutchings 1999; Nakamura et al. 1999; Waltman et al. 2006; Wang et al. 2010a, b; Adams et al. 2012) of constructed or natural wetland systems. Their research results demonstrated the configurations’ rationality and capacity for sewage treatment or water restoration. In addition, artificial wetlands are far more effective than water sewage disposal works. They also reduce the burden of responsibility in water allocation and biodiversity protection. Usually, a wetland network, a systematic process that links different patch wetlands (as nodes) by linear wetlands (as edges or corridors), would be designed to implement the ecological function and achieve the goal of protective wetland ecosystems (Cui et al. 2012; Yang & Cui 2012; Zhang et al. 2012). AFIs with aquatic macrophytes would have the potential to make up the patches and to comprise the materials for

Figure 2 | Growth characteristics of different species measured in June 2012 after 50 days growth. AR: dwarf cattail (T. minima) and yellow-flowered iris (I. wilsonii) on AFIs with radiation pattern, AP: dwarf cattail (T. minima) and yellow-flowered iris (I. wilsonii) on AFIs with annular pattern, BR: watermifoil (M. spicatum) and water shallot (S. tabernaemontani) on AFIs with radiation pattern, BP: watermifoil (M. spicatum) and water shallot (S. tabernaemontani) in AFIs with annular pattern, CR: dwarf cattail (T. minima), yellow-flowered iris (I. wilsonii) and watermifoil (M. spicatum) on AFIs with radiation pattern, and CP: dwarf cattail (T. minima), yellow-flowered iris (I. wilsonii) and watermifoil (M. spicatum) in AFIs with annular pattern.
corridors if they were designed in keeping with the surrounding landscape and natural characteristics. In general, constructed wetland technologies, as a kind of natural remediation technology, should be designed following the natural landscape pattern. Hence, composite disposition needs to be generalized. Jing et al. (2010) tested the effectiveness of different models in removing COD, TN and TP, concluding similar results with other research.

Figure 3 | Mean concentration for PH, COD, PO₄³⁻, NO₃⁻, TN, TP, for each treatment throughout the batches (01 – 06). Initial concentrations (PH, COD, NO₃⁻, PO₄³⁻, TN, TP) are 8.40, 38.15, 1.29, 1.35, 2.75 and 0.49 mg/L. Sixty-day samples were only collected for some treatments.
They found the poly-culture model for compound wetlands was preferable. According to the results of variance analysis, the impact of different plant configurations on removal rates of COD and the impact of different patterns on removal rates of PO$_4^{3-}$ were of significant difference. On the basis of multiple comparisons of plant configuration by LSD, the following conclusions can be reached: (1) the configurations of TM + WI and MS + ST made a highly significant difference on PO$_4^{3-}$ (P-value = 0.041) removal; (2) the configurations of TM + WI and TM + WI + MS made a highly significant difference to TN (P-value = 0.034) and COD (P-value = 0.019) removal; and (3) the disposition of MS + ST and group TM + WI + MS made a highly significant difference to COD (P-value = 0.037) purification. In addition, most of the P-values calculated were less than or close to 0.1. In other words, the difference on water treatment of different configurations was obvious in many aspects. By using combined multiple comparisons with estimated average marginal mean, the result showed some important information: (1) the configurations of group MS + ST and group TM + WI + MS had a similar ability to remove TN and TP, and were obviously stronger than that of TM + IW; (2) MS + ST performed significantly better than other groups on PO$_4^{3-}$ purification; and (3) TM + WI + MS had a significant advantage in COD removal. On the other hand, different patterns also demonstrated a clear difference in purification. The difference is most obvious on COD, PO$_4^{3-}$, and TN removal; and the radiation pattern was better than the annular pattern in water purification in almost all situations, except COD treatment in MS + ST. In addition, the growth situation can reflect the purification efficient (Cheng et al. 2009). In practical terms, root activity and underground biomass increment have a significant correlation with phosphorus removal and the total increment of biomass and plant height have a correlation with nitrogen removal. As can be seen, all species grew more with the radiation pattern in almost all groups and this proved the advantage of this pattern on sewage treatment, indirectly.

### CONCLUSIONS

In accordance with the experiment and analysis, the research provides some advice for improving constructed AFI wetland technology on sewage treatment and water body restoration in Beijing and other areas with similar climate conditions. First, the radiation pattern should be widely adopted. Second, watermifoil (M. spicatum) and water shallot (S. tabernaemontani) should be chosen when the main pollutants are TN, TP or PO$_4^{3-}$. Finally, dwarf cattail (T. minima), yellow-flowered iris (I. wilsonii) and watermifoil (M. spicatum) should be used in constructed wetlands when the major function is COD or NO$_3^-$ removal.
However, there are some questions that need to be addressed in future studies. First, the experimental scale in the current study was limited to the laboratory, while the difference among different plant arrangements might be magnified or contracted on a larger scale. For instance, the hydrology may influence the effect of purification (Austin et al. 2007). So, the correlation of removal efficiency between different scales should be investigated. The temperature, depth and pollutant concentration may be key factors when experiments are carried out in a lake and flow rate should also be taken into consideration in rivers. Moreover, many studies have proven the purification capacity of constructed wetlands in natural water areas, but some parameters are still lacking. The fluctuations in pollutant concentration, flow velocity and water depth may be major impact factors and affect the purification performance of AFIs. In order to improve AFI technology for practical application, it is necessary to design relevant experiments in natural water areas.

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