Nutrient removal at a drinking water reservoir in China with an algal floway

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ABSTRACT

An experimental algal floway (5 m² in area) for water quality management was studied seasonally over an annual cycle in 2013 at a drinking water reservoir in Fujian Province, China. Algal productivity averaged 21.4 ± 8.5 g dry weight m⁻² d⁻¹ across all seasons. Dominant algal taxa were Bacillariophyta (mainly Melosira sp.). Ash content of the algal biomass was high (82.4–91.4%) perhaps in part due to high concentrations of diatom silica frustules. Nutrient (N and P) removal was assessed by multiplying algal biomass productivity rate by the nutrient content of the algal biomass. Average nutrient removal rates across seasons were 212 ± 28 mg N m⁻² d⁻¹ and 36 ± 6 mg P m⁻² d⁻¹. No seasonal difference was found for either algal productivity or N removal rates but P removal rates were significantly higher in the spring and summer compared with fall and winter. N and P removal rates were positively correlated with algal productivity. Algal floway performance, in terms of algal productivity and nutrient removal rates from this study, for this subtropical site, was higher than most published studies, which were largely from temperate zone locations in the United States. Based on this study, scaling calculations suggest that the area of algal floway required to treat 1 m³ d⁻¹ of water in the fall and winter would be more than twice the size (~22 m²) than in the spring and summer (~11 m²).

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1. Introduction

Human activities have contributed to a substantial degradation of water quality in aquatic ecosystems worldwide. With an increasing demand for low-cost technologies to improve the water quality in degraded aquatic ecosystems, the ecological engineering approach which applies controlled ecosystems designed specifically for water treatment has been used to solve this problem (Cai et al., 2013; Guterstam and Todd, 1990; Higgins and Kendall, 2012; Mitsch and Mander, 1997; Ou et al., 1997; Passeport et al., 2013; Troell et al., 1999). Algal Turf Scrubber™ (ATS), one algal-based treatment system, invented by Dr. Walter Adey in the late 1970s (Adey, 1982; Adey and Loveland, 2007), can utilize algal photosynthesis and growth to control a wide variety of water quality parameters. The ATS technique removes nutrients (nitrogen and phosphorus) and carbon dioxide and increases DO concentration of water columns (Adey et al., 2011; Christenson and Sims, 2011).

Compared to other treatment processes, algae are capable of using solar energy and have higher photosynthetic potential than higher-level plants. As the byproducts of the ATS technique, microalgae can be used to produce biofuels thereby increasing the economic benefit when the technique applied at a large scale (Cai et al., 2013).

The ATS technique has been applied in water treatment for more than 30 years, since it was initially used as a water management technology in microcosm and mesocosm research (Adey et al., 1996; Craggs et al., 1996a, 1996b). In recent years, large scale ATS systems have been used for nutrient removal ranging from aquaculture and tertiary treatment of sewage to agricultural drainage water and dairy manure (Adey et al., 2011, 2013; D’Aiuto et al., 2015; Kangas and Mulbry, 2014; Mulbry et al., 2008, 2010; Pizarro et al., 2002; Sandefur et al., 2011). However, there are challenges and some limits to the widespread implementation of such system. So far, most studies on ATS were in temperate region of United States. Studies in other climatic zones, especially in subtropical region, have not been reported. Productivities of algae is typically influenced by various factors including the nutrient supply and recycling, gas transfer and exchange, culture integrity and site-specific environmental conditions (i.e., temperature,
sunlight) (Adey et al., 2011) Therefore, it is necessary to apply the ATS technique in other climatic regions to further assess its potential in solving large-scale water quality problems.

Nutrient over-enrichment is of increasing concern in subtropical coastal regions, which are often populated areas experiencing rapid development and widespread changes to the aquatic environment (Chen and Hong, 2012). For example, the Jiulong River in Southeast China has suffered greatly from animal wastes and agricultural runoff, resulting in eutrophication and algal blooms in reservoirs and the estuary (Chen et al., 2008, 2013; Li et al., 2011). Integrated watershed management in this area calls for novel techniques to remove excess nutrients to improve water quality and secure drinking water supply. In this study a joint program between Xiamen University and the University of Maryland designed and tested a modified ATS in the Jiulong River (Jiangdong Reservoir), an eutrophic river in subtropical China. The aim of this study was to provide a preliminary assessment of the ATS technology with its initial application in China. A modified version of an ATS, without pulsing flow, was studied in this work. This is a first step toward a large-scale application to improve water quality and to produce algal biofuels with this kind of ecologically engineered technology. Based on the results from four seasonal field experiments in 2013, this study provides a preliminary quantification of algal growth rates (algal productivity), chemical and biochemical composition of the algae, and nutrient removal performance. Key factors affecting algal flowway performance, and recommendations concerning development of large scale ATS application in the Jiulong River and other aquatic systems in China are discussed.

2. Materials and methods

2.1. Description of study site

The Jiulong River, which is located in southeast China, is the second largest river in Fujian Province and it has a watershed of 14,740 km². Three tributaries (North River, West River, and South River) discharge water into Xiamen Bay through the estuary. This study targets the North River, which is the main tributary with a channel length of approximately 274 km. The watershed covers four cities/counties (Longyan, Zhangping, Hu’an and Changtai) and a part of Zhangzhou city, with a population of about 1.5 million. The outlet (Jiangdong Reservoir, as drinking water source for Zhangzhou City and Xiamen City) of the North Jiulong River watershed (N24°31’13.63”, E117°47’10.72”) was selected as the site for this study (Fig. 1). Because of the relatively remote location of the experimental system, transportation was limited and it was operated seasonally rather than continuously.

2.2. Experiment and sampling

A pilot-scale algal flowway with a 5 m² screen growing area was constructed at a 1% slope in a field along the reservoir margin (Fig. 1). A submersible pump in the reservoir delivered water at an average flow rate of 46.5 L.min⁻¹ to the inlet of the algal flowway. The water flows over the algal turf before draining from the unit back into the reservoir. Algae, as periphyton, attached and grew to a plastic mesh screen that is placed on the bottom of the flowway. Bricks were placed on the screen to distribute the water flow which had a depth of approximately 50 mm. This was a modified ATS since it did not have a mechanism for pulsing the water input; because of this feature the system is referred to as an algal flowway in this paper.

Four experiments were carried out in 2013 covering four seasons (spring: March 10th–20th, summer: June 25th–July 13th, fall: October 10th–28th, and winter: December 3rd–24th). The system operation stopped and restarted for each seasonal sampling event. Seasonally, water and periphyton samples were manually collected during three cycles of cultivation and algal biomass was harvested and measured at the end of each cycle. Each cultivation cycle lasted 3–9 days, depending on a subjective judgment of algal density by faculty of the Xiamen Environmental auto-monitoring station at the Jiangdong Reservoir where the system was located.

Before each harvest, water quality parameters (water temperature, DO, pH) were monitored in the inlet and outlet of the flowway using a WTW Portable Multi Parameter (Multi 3430). Following filtration through 0.7 μm nucleopore GF/F membranes, water samples from the inflow were stored in 100 mL polyethylene bottle. Then the pump was turned off so that water would drain from the system (in approximately 15 min). A small volume of periphyton on the mesh screen at both the inflow and outflow were collected and preserved with formaldehyde for identification. Then the wet algae biomass were scraped to the outflow area using brush and introduced to a large bucket. Sump water was thoroughly agitated to resuspend sediment and algal fragments. The total volume was measured and recorded. A 1000 mL sample of the harvested algal biomass was collected. All samples were stored in an insulated container with ice and delivered to the laboratory at Xiamen University immediately after harvest. Water samples were frozen at −20 °C in the lab before nutrient analysis.

2.3. Lab analysis

2.3.1. Algal biomass treatment and analysis

The algal biomass was air-dried with a fan first, then oven-dried (70 °C) for 24 h. Dry weight (biomass) was determined with an electronic balance. The growth rate of the algae A (g m⁻² d⁻¹) was calculated with Eq. (1), where dried weight (g) equals the dried weight of the 1000 mL sample multiplying total volume of algal biomass recorded in field. Subsample of dried algae was ashed at 550 °C for 2 h in a muffle furnace and reweighed to determine the ash content. The ash content (%) was calculated with Eq. (2) and it reflects the magnitude of inorganic sediment or suspended solids in the flowing water along with diatom frustules.

\[
A = \frac{\text{dried weight (g)}}{\text{ATS area (m²)/cultivation days (d)}} \quad \text{(1)}
\]

\[
\text{Ash content} = \frac{\text{ashed weight (g)}}{\text{oil-en-dried weight (g)}} \times 100 \quad \text{(2)}
\]

2.3.2. Chemical analysis and calculation of nutrient removal rate

After mechanical grinding, algal biomass samples (~30 mg) were directly analyzed for total nitrogen (TN) and total organic carbon (TOC) by CHNS/O elemental analyzer (PE2400 SeriesII). Following ashing of algal biomass samples (100 mg), which converted all P to phosphate, extractions with hydrochloric acid (1 mol L⁻¹) were oscillated for 18 h and centrifuged for 10 min (4000 rpm). The treated liquid supernatant was diluted to an appropriate concentration range and then was analyzed with a spectrophotometer for P content in algal biomass. River water samples were analyzed using standard spectrometric methods (State Environmental Protection Administration (SEPA), 2002). Concentration of nitrate (NO₃⁻-N), ammonium (NH₄⁺-N), and dissolved reactive phosphorus (DRP) were determined by segmented flow automated colorimetry using the manufacturer’s standard procedures (San++ analyser, The Netherlands). The precision for nutrient analysis was estimated by repeated samples and the relative error was less than 5%. For quality control in laboratory, a standard reference material (SRM) provided by Ministry of Environmental Protection of China was used to check the instrument performance.
Nutrient removal rates were calculated by multiplying the algal productivity by the C/N/P content in biomass (Eq. (3)).

\[
\text{Nutrient removal rate} \ (\text{g nutrient m}^{-2} \text{d}^{-1}) \nonumber \\
= \text{biomass productivity (g dry weight m}^{-2} \text{d}^{-1}) \nonumber \\
\times \text{nutrient content (\%)} \nonumber \\
\]  

(3)

2.3.3. Algae species identification and cell density counting

In order to identify the algal species and cell density, the preserved periphyton samples were observed microscopically (400× or 1000× magnification; Nikon 90i). Detailed methods used for algal cell counts are given by Hu and Wei (2006).

2.4. Statistical analysis

Statistical analysis was performed using SPSS 17.0 to assess the relationships between parameters and explore the main factors controlling ATS performance (algal productivity and nutrient removal rate). Mean and standard error (±SE) represented the variation in the measurements. We used one-way ANOVA (LSD test) to identify significant differences (p < 0.05) among groups of interest.

3. Results

3.1. Water quality

Water temperature and precipitation were plotted over experiment periods (Fig. 2). The average water temperatures of March, July, October and December in 2013 were 19.3 °C, 26.9 °C, 24.0 °C, and 15.0 °C, respectively. The recorded rainfall during the four experimental periods was 9.3 mm, 65.2 mm, 0 mm, and 67.1 mm, respectively. Nutrient concentration in the flowing water ranged from 0.71 to 2.99 mg L\(^{-1}\) for NO\(_3\)-N, from 0.10 to 1.05 mg L\(^{-1}\) for NH\(_4\)-N and from 0.001 to 0.125 mg L\(^{-1}\) for dissolved reactive phosphorus (DRP). The extreme low DRP concentration (0.001 mg L\(^{-1}\)) was observed during the first cultivation cycle in March when an algal bloom occurred in the reservoir (in situ sensor showing Chl-a > 40 μg L\(^{-1}\)) (data from Jiulong River auto-monitoring station of the Xiamen Environmental monitoring Center). We speculated that the phosphate should have been depleted.

During the four seasonal cultivation experiments, pH values changed from 7.01 ± 0.2 to 7.42 ± 0.39 and DO varied from 7.24 ± 1.13 mg L\(^{-1}\) to 8.75 ± 0.89 mg L\(^{-1}\). Both pH and DO were generally higher in the outflow water after passing through the algal turf compared with the inflow water, except DO in the first cycle of March and pH in the last cycle of December (Fig. 3). A large increase of DO was found in Cycle 1 in summer (July), and in cycle 3 in other seasons with a lower water temperature. The pH of the outflow water was significantly different between spring and summer (ANOVA, p < 0.05), while there is no significant difference of pH in outflow water among four seasons. There was no seasonal variation of DO concentration in both inflow and outflow water (ANOVA, p > 0.05). The difference of water quality between inflow and outflow is a function of the length of the system (or turnover time) (Ady et al., 2011). Since the outflow we used was relatively short (10 m), no much change in water quality from inflow to outflow can be detected.

3.2. Algal productivity and composition

Average total algal productivity (A) from all experiments was 21.4 ± 8.5 g m\(^{-2}\) d\(^{-1}\) (Table 1). The ash content was high (82.4–91.4%) in the harvested solids. The averaged total algal productivity of the three cycles in each season was 22.3 g m\(^{-2}\) d\(^{-1}\) (spring), 25.4 g m\(^{-2}\) d\(^{-1}\) (summer), 17.6 g m\(^{-2}\) d\(^{-1}\) (fall), and 20.6 g m\(^{-2}\) d\(^{-1}\) (winter), respectively. The lowest algal productivity was usually observed in the first harvest cycle regardless of season and a higher value was found in the later two cycles. The overall algal productivity showed no seasonal difference (ANOVA, p > 0.05). The maximum algal productivity (33.1 g m\(^{-2}\) d\(^{-1}\)) was observed in winter experiment (cycle 3).

The dominant periphyton species on the algal turf were relatively consistent with seasons or with location on the flowway (inlet versus outlet) (Fig. 4). One genus of filamentous diatom, Melosira sp. (Bacillariophyta), dominated the samples, in terms of cell density, comprising 66% of the total in July, 85% of the total in October and 80% of the total in December. The summer algal community was the most diverse with a higher representation of blue-green algae (Cyanophyta) than in the other seasons. Fig. 4 illustrates the relative abundances of algal phyla during the seasons when cell were counted, averaged across the inlet and outlet sample sites on the flowway.
Fig. 2. Change in water temperature and precipitation during cultivation period in four seasons. The sampling times are shown as circles; real-time water temperature and hourly rainfall data from Zhangzhou city was obtained from the Water Environmental Information System – Jiulong River watershed, [http://222.76.242.48:3505/](http://222.76.242.48:3505/). There is no rainfall in October cultivation.

Fig. 3. Comparison of water quality parameters (DO and pH) between the inflow and outflow water through the 10 m long algal floway. Each bar is for a single measurement at harvested date.
Table 1
Cultivation days, ash content of dried algal biomass, and total algal productivity for the four seasonal experiments (2013).

<table>
<thead>
<tr>
<th>Season</th>
<th>Sampling date</th>
<th>Cultivation days (d)</th>
<th>Ash content (%)</th>
<th>Total algal productivity (g m⁻² d⁻¹)</th>
<th>Ash-free algal productivity (g m⁻² d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>3/13/2013</td>
<td>3</td>
<td>82.4</td>
<td>13.5</td>
<td>2.37</td>
</tr>
<tr>
<td></td>
<td>3/17/2013</td>
<td>4</td>
<td>83.5</td>
<td>25.7</td>
<td>4.23</td>
</tr>
<tr>
<td></td>
<td>3/20/2013</td>
<td>3</td>
<td>84.9</td>
<td>27.6</td>
<td>4.18</td>
</tr>
<tr>
<td>Summer</td>
<td>7/1/2013</td>
<td>6</td>
<td>89.3</td>
<td>23.7</td>
<td>2.54</td>
</tr>
<tr>
<td></td>
<td>7/10/2013</td>
<td>6</td>
<td>86.8</td>
<td>30.7</td>
<td>4.04</td>
</tr>
<tr>
<td></td>
<td>7/13/2013</td>
<td>3</td>
<td>87.9</td>
<td>21.8</td>
<td>2.63</td>
</tr>
<tr>
<td>Fall</td>
<td>10/15/2013</td>
<td>5</td>
<td>87.1</td>
<td>7.0</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>10/22/2013</td>
<td>7</td>
<td>87.7</td>
<td>19.1</td>
<td>2.34</td>
</tr>
<tr>
<td></td>
<td>10/28/2013</td>
<td>6</td>
<td>87.6</td>
<td>26.7</td>
<td>3.30</td>
</tr>
<tr>
<td>Winter</td>
<td>12/12/2013</td>
<td>9</td>
<td>88.2</td>
<td>7.2</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>12/19/2013</td>
<td>7</td>
<td>91.4</td>
<td>21.5</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>12/24/2013</td>
<td>5</td>
<td>89.0</td>
<td>33.1</td>
<td>3.63</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>5.3</td>
<td>87.2</td>
<td>21.4</td>
<td>2.37</td>
</tr>
</tbody>
</table>

![Figure 4](image-url)

Fig. 4. Comparison of algal densities on the algal flowway from the Jiulong River Reservoir in Fujian Province, China in 2013. Densities are summed across three harvest cycles for each month except March when data was not available.

The nutrient content of the algae showed seasonal patterns (Fig. 5). The mean N content in the biomass among three cycles was 1.31% and 0.84% in spring and summer, 0.89% and 0.86% in fall and winter. The mean percentage of P in the algal biomass from spring to winter was 0.24%, 0.20%, 0.09%, and 0.11%, respectively. The N:P ratio (which reflects the nutrient adsorption and utilization by algal community) in fall and winter exceeded the Redfield ratio (16:1) while it was lower than the Redfield ratio in spring and summer. Nevertheless, the C:N ratio stayed around 7–8 for all experiments.

![Figure 5](image-url)

Fig. 5. The biogenic element ratios (by mole) of the harvested algal biomass. Dashed lines indicate the Redfield ratio (106:16N:1P).

3.3. Nutrients removal rate in different seasons

Average nutrient removal rates for all experiments were 212 ± 28 mg N m⁻² d⁻¹, and 36 ± 6 mg P m⁻² d⁻¹. The N removal rate declined gradually from spring to fall and winter, ranging from 283 mg N m⁻² d⁻¹ to 161 mg N m⁻² d⁻¹. There was no significant difference among seasons. P removal rate declined from 54 mg P m⁻² d⁻¹ to 18 mg P m⁻² d⁻¹, with a significant difference between spring/summer and fall/winter (p < 0.05) (Fig. 6). In addition, a varied nutrient removal rate during the cultivation cycle sequences was found (Fig. 6). The nutrient removal rates were relatively low for the first cycle compared to the following two (Fig. 6), corresponding to the lower algal productivity (Table 1). In spring (March) and summer (July), the algal flowway system achieved the maximum removal rate in Cycle 2 but it declined in Cycle 3. In contrast, in fall (October) and winter (December), nutrient removal rates increased gradually with cultivation cycle sequences.

Given the assumption that raw water in the reservoir (inflow water) should be reduced to a low level via cyclic treatment to meet for the national water quality criterion (grade III for drinking water source) (GB3838-2002), algal flowway system size and cultivation time required for treating 1 m³ per day of raw water were calculated as 16 m² and 3 m³, respectively (Table 2). The algal flowway size and cultivation time required in winter and fall (>22 m²) were higher than other two seasons (<11 m²). Because of the low nutrient removal rate in winter, the algal system required in winter should be 3–4 times larger than in spring or summer. A longer...
Table 2

Resources required for treating river water using the ATS system.

<table>
<thead>
<tr>
<th>Season</th>
<th>Raw water concentration* (mg L⁻¹)</th>
<th>Reduced concentration required* (mg L⁻¹)</th>
<th>Nutrients removal rates by ATS (mg m⁻² d⁻¹)</th>
<th>ATS size and time required for treating 1 m³ water (m² d⁻¹)</th>
<th>Time required for treating 1 m³ water with 100 m³ ATS (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DIN</td>
<td>DRP</td>
<td>DIN</td>
<td>DRP</td>
<td>N</td>
</tr>
<tr>
<td>Spring</td>
<td>2.79</td>
<td>0.002</td>
<td>2.09</td>
<td>-0.013</td>
<td>283</td>
</tr>
<tr>
<td>Summer</td>
<td>1.91</td>
<td>0.075</td>
<td>1.21</td>
<td>0.060</td>
<td>214</td>
</tr>
<tr>
<td>Fall</td>
<td>3.30</td>
<td>0.070</td>
<td>2.60</td>
<td>0.055</td>
<td>161</td>
</tr>
<tr>
<td>Winter</td>
<td>2.41</td>
<td>0.108</td>
<td>1.71</td>
<td>0.093</td>
<td>191</td>
</tr>
</tbody>
</table>

* Here and nutrients removal rates indicate mean value of three cycle cultivation.

The reduced concentration required is assumed to be the difference from the water quality criterion (grade III for drinking water source). According to China National criterion of Environmental Quality for Surface Water (GB3838-2002), TN and TP should be less than 1 mg L⁻¹ and 0.005 mg L⁻¹ for reservoir water. Based on our previous measurements in the Jiangdong Reservoir (unpublished data), a ratio of DIN/TN = 0.7, DRP/TP = 0.3 were used to keep the calculation consistent with nutrient forms.

ATS size and time required for treatment of 1 m³ water (m² d⁻¹) = 1 m³ × reduced concentration required (mg L⁻¹) × nutrient removal rates (mg m⁻² d⁻¹).

Fig. 6. Nutrient removal rates of the algal flow over seasons. (a) Nitrogen and (b) phosphorus. The mean removal rates were shown as cycles and error bar indicates one standard error (SE). Significant difference between seasons was marked with a and b (ANOVA, p < 0.05).

cultivation time is needed to remove N versus P in order to meet the required water quality, because TN concentration in the reservoir far exceeds water quality criterion compared with TP. If a 100 m² algal system (probably the most appropriate size for this mountain area with limited land source) was used for treating 1 m³ of polluted river water, the cultivation would take less than 0.25 days. 2.5 h is enough in spring and summer when the algal system has a greater performance in removing nutrients from the water.

4. Discussion

4.1. Key factors controlling algal flow performance

Algal productivity (Table 1) and nutrient removal rates (Fig. 6) can be used to valuate the algal flow performance over seasons. Algal productivity can be influenced by those factors varying with season. While the algal productivity peaked in winter (high ash content), the ash-free algal productivity (growth rate of algae) appeared to slightly increase with water temperature but the correlation was weak (Fig. 7), indicating that temperature might not be the only factor responsible for the seasonal variation of system performance. In terms of nutrient supply, the ash-free algal productivity is negatively correlated with NH₄-N ($R^2 = 0.93$) and DRP ($R^2 = 0.71$). Algal productivity seemed to increase with NO₃-N but the correlation was not statistically significant ($p > 0.05$). Diatoms were the dominant periphyton on the algal turf in all four seasons (Fig. 4). A study suggested that rapid proliferation of diatoms was strongly linked with increasing NO₃-N (Lomas and Gilbert, 2000).

We speculated that NO₃-N (dominant form of inorganic N) in the Jiulong River was very rich and not likely to be limiting factor that controls the seasonal variation of algal productivity. More experiments and measurement are needed to confirm this statement. As other factors may influence algae growth in field (discussed below), key factors controlling algal flow performance over the seasons could not be confirmed, and need further study.

Nutrient removal rate was the product of algal productivity and nutrient content in biomass. A stronger correlation was found between N removal rate and algal productivity ($R^2 = 0.83$) than between N removal rate and N content in the biomass ($R^2 = 0.60$), whereas P removal rate was positively correlated with algal productivity ($R^2 = 0.71$) as well as P content in the harvested biomass ($R^2 = 0.77$) (Fig. 8). Therefore, algal productivity plays a determinative role in controlling the seasonal variation in the N removal rate, while algae P content and algal productivity together control the seasonal variation of the P removal rates. Algal productivity can explain more than 80% of the seasonal variation in N removal rate due to the less variable algal N content over the seasons (coefficient of variation (CV) = 0.25) compared to the algal P content (CV = 0.43). In this instance, the varied nutrient ratio of periphyton fragment on the algal turf over season (Fig. 5) mainly tied to the changing algal P content (higher P content in spring and summer, and lower P content in fall and winter). This could be caused by subtle changes in periphyton species. Some algal species absorb nutrients more efficiently, e.g., Pandora and Synedra, which were relatively abundant on the algal system in spring and summer. The changing nutrient ratios (Fig. 5) also suggested different utilization of nutrient forms (N and P) as the algal community changes over the seasons.

The varied algal productivity between the continuous cycles was interactively affected by the changing weather condition (sunlight or rainfall) and ecosystem succession during the cultivation cycles. Algal growth can also be influenced by daily weather and sometimes by system failures. For instance, there were some rainfall and foggy days during the experiments, and the electricity of submersible pump was temporally powered-off during the second cycle in July (Fig. 2b). The algal bloom event that occurred in March also changed the algal community and nutrient supply in flowing water. These unpredictable factors are responsible for the variation of algal productivity between cycles. The lowest algal
productivity was usually observed in the first cycle because there was no periphyton initially on the screen. In the following two cycles, there were some attached algae left on the turf that stimulate periphyton growth and shorten the cultivation cycle. Given the subjective determination of harvest timing (3–9 days in this study), algal growth was probably affected by the time interval between harvest cycles.

4.2. Application potential of ATS technology in China and recommendations

The algal productivity and nutrient removal rate both fell into the higher portion of the reported values from US studies (Table 3). The reported data show a wide range in nutrient removal rates among various study sites and algal systems, which could be explained by the climate and system condition. Higher nutrient removal rates were found in the Jiulong River, which is nutrient rich and located in a subtropical area with warm climate, but it was still lower than the case of the Southern Florida system (HydroMentia Inc., 2005). The nutrient removal rates in natural waters (river or stream) were usually greater with pollution from anthropogenic activities (discharging human and animal waste). Compared to the other comparison studies listed in Table 3, the lack of wave surge on our system could be a factor in lower performance. Typically, sampling on algal floway is performed on a mature turf, which requires at least 6 weeks of startup time for growth and colonization and a year for complete maturity. Our system operation stopped and restarted for each seasonal sampling event, resulting in an underestimated productivity and nutrient removal that rely upon sampling from a startup/colonization phase rather than

![Graphs and equations](image)

**Fig. 7.** Relationships between ash-free algal productivity and water temperature, nitrate, ammonium, and DRP. Values are averaged of three cycles in each season. Error bar indicates one standard error (SE).

**Fig. 8.** Relationships between nutrient removal rates and algal productivity, nutrients content in biomass among different cycles.
from a phase of steady-state growth. In addition, the local algal community and associated nutrient content may be different. The proportion of diatoms in freshwater US cases was less than 90% (see Kangas and Mulbry (2014) and Sandefur et al. (2011)), not as large as the China site (>90%) described here. Given that green or blue-green algae could take up more nutrients, relatively less green or blue-green algae in the Jiulong River algal system could have lowered the algal productivity and nutrient removal rate. Flow rate might also have influenced system performance. Although the flow rate used in this study (98 L min⁻¹ per meter of flowway width) was within the range of values reported in other studies, a higher flow rate may have increased performance of the system (Kangas and Mulbry, 2014).

In the long term our goal is to develop an option for converting algal biomass into biofuels. Many efforts are underway in this regard, but commercialization is pending (Chisti and Yan, 2011; Georgianna and Mayfield, 2012; Pienkos et al., 2011; Service, 2011; Wijffels and Barbosa, 2010). One limitation to biofuel generation from the flowway studied here is the high ash content of the algal biomass. One design that might reduce the ash content would be to run water through a settling basin to reduce suspended inorganic sediments before it reaches to the algal flowway, but this approach will not affect silica in the diatoms growing on the screens. Future experiments are planned to reduce the ash content and to develop a viable option for biofuels as a byproduct of the water quality improvement function of the algal-based technologies.

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