water

MDPI

Article

Ecological Efficiency of the Mussel *Hyriopsis cumingii* (Lea, 1852) on Particulate Organic Matter Filtering, Algal Controlling and Water Quality Regulation

Xiaobo Yu [1,2,†], Qinglin Yang [1,2,†], Zhe Zhao [1], Xiaoqi Tang [1,2], Bo Xiong [1,2], Shengqi Su [1,2], Zhengli Wu [1,2,*] and Weizhi Yao [1,2,*]

[1] Key Laboratory of Freshwater Fish Reproduction and Development (Ministry of Education), Research Center of Fishery Resources and Environment, College of Fisheries, Southwest University, Chongqing 400715, China; yuxiaobo@swu.edu.cn (X.Y.); yang975@email.swu.edu.cn (Q.Y.); zhaozhe@email.swu.edu.cn (Z.Z.); txq19980703@email.swu.edu.cn (X.T.); xiongbo@swu.edu.cn (B.X.); sushengqi@swu.edu.cn (S.S.)

[2] Comprehensive Experimental Station of Chongqing, National Shellfish Industry Technology System, Chongqing 400715, China

* Correspondence: zh20140202@swu.edu.cn (Z.W.); yaowz@swu.edu.cn (W.Y.); Tel.: +86-23-6825-1070 (W.Y.); Fax: +86-23-6825-1196 (W.Y.)

† These authors contributed equally to this work.

Abstract: *Hyriopsis cumingii* plays an important role in aquatic ecosystems and fishery economy due to its potential value for water purification and edibleness. The present study was undertaken to reveal the short- and long-term purifying effects of *H. cumingii* on pond water. The short-term experiment results showed that total suspended solids, particulate organic carbon, and fatty acid in water were significantly eliminated by *H. cumingii*, with average percentage of filtering effect respectively reaching 22.19%, 57.48%, and 21.00% in the high-density group. Analogously, *H. cumingii* could significantly reduce phytoplankton biomass, species number, density, and chlorophyll-a concentration, especially in the control of diatoms, green algae, and cyanobacteria. Besides, electric conductivity also was significantly reduced by *H. cumingii* and its variation tendency showed a typical density-dependent effect. Similar purification effects were observed in chemical oxygen demand (COD), total nitrogen, and total phosphorus. In the long-term monitoring test, *H. cumingii* has also shown positive effects on the water transparency and the control to phytoplankton and COD in recirculating aquaculture pond. Overall, *H. cumingii* showed excellent ecological function, and the mixed breeding density of shellfish in the recirculating aquaculture pond is worth further exploration.

Keywords: *Hyriopsis cumingii*; aquatic ecosystem; water purification; freshwater

Citation: Yu, X.; Yang, Q.; Zhao, Z.; Tang, X.; Xiong, B.; Su, S.; Wu, Z.; Yao, W. Ecological Efficiency of the Mussel *Hyriopsis cumingii* on Particulate Organic Matter Filtering, Algal Controlling, and Water Quality Regulation. *Water* **2021**, *13*, 297. https://doi.org/10.3390/w13030297

Academic Editor: Michele Mistri
Received: 22 December 2020
Accepted: 21 January 2021
Published: 26 January 2021

1. Introduction

Human beings have complex social, economic, and ecological dependence on freshwater ecosystems, but the development of intensive aquaculture has brought potential threats to freshwater environments [1–3].

Freshwater shellfish, as a species able to purify water, has been neglected for a long time in China, with the production of 0.20 million tons only accounting for 0.66% of total freshwater aquaculture production in 2018 due to its small scale of breeding and long economic cycle [4]. Recently, resulting from the guidance of new environmental protection policies [5], the ecological function of freshwater shellfish has gradually attracted the attention of the aquaculture industry in China. Therefore, different aquaculture modes such as "benthic or hanging aquaculture of shellfish" and "macrophytes and bivalve mixed breeding" have been mentioned and developed again for freshwater purification [6,7].

Biomanipulation is an important way to restore eutrophic water bodies in the long term and to reduce costs can continuously regulate nutrient loading through different biological methods [8]. Among them, filtration by bivalves can lead to a large decrease in phytoplankton and other particles in the water column [9]. However, the filtration rate in freshwater or seawater is varied with different shellfish species and size, salinity, temperature, particle size and concentration, density, and flow regime [10–12]. Furthermore, shellfish or other mollusks may control microbial concentrations and community structure either directly by using bacteria as a food source or indirectly by producing fecal or pseudo-fecal material that affects bacterial activity and growth [13,14]. Nevertheless, research about freshwater shellfish is still in its infancy and its ability to filter aquaculture water and related water purification mechanisms need to be studied urgently.

The bivalve mollusk triangle sail mussel (*Hyriopsis cumingii*), which belongs to the Unionidae family, is widely used for pearl production. At present, despite obvious progress in the research of genetic breeding [15], growth traits, and pearl cultivation [16], the application of *H. cumingii* for water purification are still left behind, although the culture of excessive filter-feeding bivalves may harm the balance of the ecosystem [17,18]. In recent years, the use of *H. cumingii* has been proposed as an effective strategy to control algal bloom in eutrophic water bodies, and several regulatory effects have been achieved [19]. The filter-feeding activity of *H. cumingii* may potentially support submerged macrophyte growth by reducing cyanobacterial density, but bivalve communities in natural water are in decline as a result of overharvesting [20]. Moreover, *H. cumingii* can also be used as a superior material for retrospective monitoring of eutrophication-induced environmental changes in aquatic ecosystems [21].

Overall, aquaculture water pollution is becoming a severe environmental issue throughout the world. The utility of bivalves as a bio-manipulation way to improve water quality and control algal blooms has been broadly acknowledged, but the potential purification mechanism of bivalve shells has received little attention. This study aimed to evaluate the short- and long-term impacts of *H. cumingii* on pond water. The purpose of this study was to promote the development of the ecological aquaculture model based on *H. cumingii* in suitable inland areas of China.

2. Materials and Methods

2.1. Shellfish and Experimental Design

In a short-term experiment, healthy *H. cumingii* with similar characteristics (wet weight: 74.7 ± 6.0 g, shell length: 8.2 ± 1.0 cm) were obtained from the Comprehensive Experimental Station of Jinhua, National Shellfish Industry Technology System (Zhejiang, China) and were maintained in an aquaculture pond, with temporary breeding for a month at natural temperature. Five groups with different densities of 0 individuals (CG), 3 individuals (G1), 6 individuals (G2), 9 individuals (G3), and 12 individuals (G4) were set for the short-term test of filtering water. Each group was performed in triplicate. The experiment was conducted in continuously oxygenated opaque plastic drums filled with 100 L of pond water that came from an aquaculture pond of about 15,000 m^2 on campus. The short-term experiment was carried out for a week continuously in a closed-form without fish being cultured.

In the long-term experiment of monitoring aquaculture pond, *H. cumingii* individuals were placed behind the tailwater discharge area of the recirculating aquaculture pond (total 5 flume, the total area is about 2.93 hm^2) in Xinyue Aquaculture Co., LTD, Bishan District, Chongqing, China (Figure 1). *Barbus capito* is the main fish species cultured in the flume. The average diet was about 2% of the fish's body weight. In each flume (length: 7 m, width: 2.5 m, water depth: 2 m), it was set about 500 individuals of (average wet weight: 368.9 ± 106.1 g, shell length: 15.7 ± 1.4 cm) *H. cumingii* in the purification area. Collecting of phytoplankton and water samples of the tailwater discharge area, *H. cumingii* purification area, and ecological purification area were conducted monthly except in

February and November in 2018 (15 January, 21 March, 18 April, 28 May, 20 June, 19 July, 12 August, 4 September, 11 October, 25 December), as considering with the water quality condition is stable in low-temperature season. Two independent samples were acquired and detected at a time per sampling site.

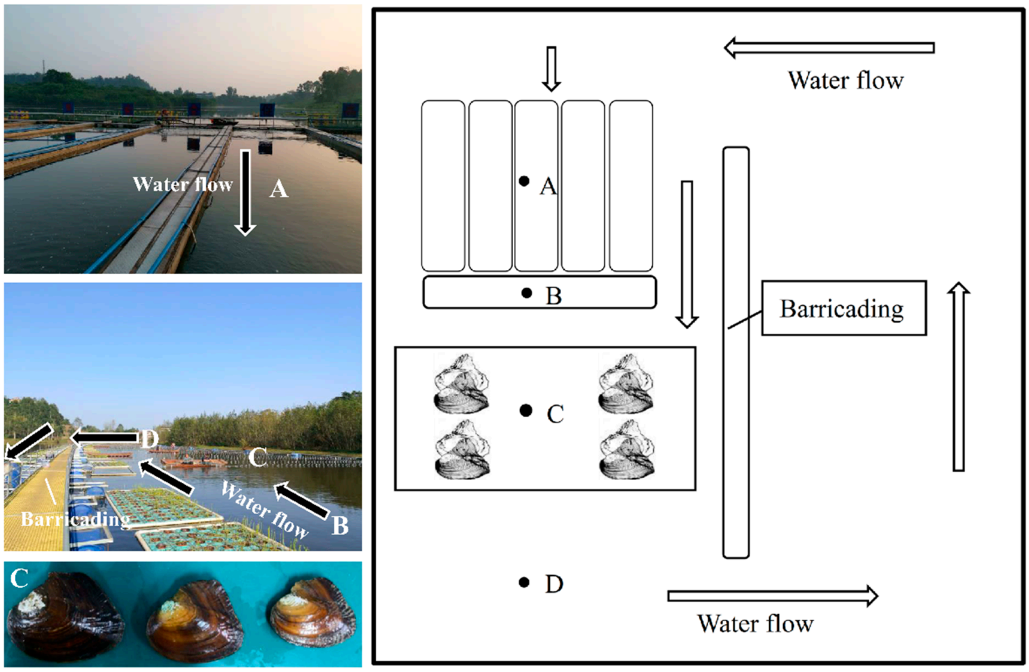

Figure 1. Schematic diagram of pond aquaculture structure and *Hyriopsis cumingii* area selection (**A**: Fish intensive culture area, **B**: Tailwater discharge area, **C**: *H. cumimgii* purification area, **D**: Ecological purification area).

2.2. Particulate Organic Matter Detection

In the short-term experiment, total suspended solids (TSS) were measured by the modulated gravimetric method [22]. Briefly, 100 mL of the water sample from each treatment was collected and adequately filtered by 0.22 μm membrane filtration, then immigrated into 103–105 °C of drying oven for an hour. After that, the samples were cooled and weighed. Particulate organic carbon (POC) was measured by the combustion oxidation and non-dispersive infrared analysis method [23] using TOC Multi N/C 2000 analyzer (Analytik Jena, Germany). Fatty acid (FA) was determined by LC-20A HPLC System (Shimadzu, Tokyo, Japan). A more detailed description is given as follows: each 1 L water sample was sufficiently extracted using the chloroform-methanol mixture and concentrated using rotary evaporators. Then samples were collected and dissolved in mobile phase solution ($V_{Methanol}$: $V_{Monopotassium\ phosphate\ solution\ (0.02\ M)}$ = 5.95) for fatty acid determination (SPD-20A UV detector, Shimadzu, Tokyo, Japan) at 210 nm, with three replicates. The percentage of filtering effect on particulate organic matter (TSS, POC and FA) was calculated according to the following equation:

$$F = \left(1 - \frac{P_i}{P_C}\right) \times 100\% \quad (1)$$

where F is the percentage of filtering effect; P_i is the particulate organic matter concentration in the treatment group; P_c is the concentration in the control group.

2.3. Chlorophyll-a and Phytoplankton Quantitative Detection

To explore the effects of *H. cumingii* on chlorophyll-a (Chl-a), each 0.5 L water sample of control and *H. cumingii* groups were collected in the short-term experiment, then filtered with 0.45 μm filter membrane and extracted with 90% acetone, centrifuged at 3500 rmp and each supernatant was removed. All samples were measured following acetone spectrophotometry (Khaleghi, 2020). The calculation formula is shown as follows:

$$\text{Chl-a} = (11.85 \times (A_{664} - A_{750}) - 2.16 \times (A_{645} - A_{750}) + 0.10 \times (A_{630} - A_{750})) \times V_1 \times V \times \delta \quad (2)$$

where A is the absorbance at different wavelengths; δ is the optical spectroscopy path length of cuvette; V_1 and V are the water sample volume and extraction volume, respectively.

The phytoplankton examination was performed in the short- and long-term experiments. The detailed description is given as follows: 1 L of water samples was collected and preserved immediately with Lugol's iodine solution, precipitated for 24 h, and then concentrated to 50 mL volume. The phytoplankton qualitative and quantitative examination was assessed by observing and counting with a microscope (Leica DM500, Wetzlar, Germany). The identification of phytoplankton genus and species was conducted by referring to "The common phytoplankton atlas of Chongqing region of the three gorges reservoir area" and "The common freshwater phytoplankton algae atlas of China" [24,25]. Phytoplankton density, biomass, and statistical calculations were carried out according to pieces of literature [26,27] and the quantitative formula of phytoplankton is given as follows:

$$C = N \times \frac{S_c}{S_f \times n} \times \frac{V_1}{V_2 \times V} \quad (3)$$

where C is the phytoplankton density; N is the number of phytoplankton in the observation field; S_c is the area of the haemocytometer; S_f is the area per view; n is the number of views per slice; V_1 is the volume after concentration; V_2 is the volume of the counting box and V is the volume before concentration.

Phytoplankton biomass (PB) was calculated by methods of cell volume conversion based on its size and average density [28]. Moreover, the species diversity and evenness were analyzed by using the Shannon-Wiener index (H). The biological diversity was calculated according to the following equation [29].

$$\text{H}' = -\sum_{i=1}^{n} (n_i/\text{N})\ln(n_i/\text{N}) \quad (4)$$

where n_i is the individual number of alga i, N is the total number of all species at each *H. cumingii* group.

2.4. Hydrochemical Parameters Detection of Samples

Water samples were collected and brought back to the laboratory for analysis of water quality according to relevant national standards [30]. In the short-term experiment, electric conductivity (EC) was monitored by a portable dissolved oxygen meter (HQ30D, HACH Company, USA). In the long-term experiment, water temperature and transparency were assessed using a water thermometer and Secchi disc, respectively. Moreover, total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD) were used for the quantitative evaluation of the trophic state in the pond water. Among them, TP was measured at 700 nm by the ammonium molybdate spectrophotometric method [31] with an ultraviolet spectrophotometer (UV-1800, Shimadzu, Japan). TN was measured at 220 nm and 275 nm by the alkaline potassium persulfate method [32] with an ultraviolet spectrophotometer (UV-1800, Shimadzu, Japan). Meanwhile, COD was measured by the dichromate method [33], and the calculation equation is shown as follows:

$$\mathrm{COD}(\mathrm{O_2}, \mathrm{mg\ L^{-1}}) = [(V_0 - V_1) \times \mathrm{c} \times 8\ \mathrm{g/mol} \times 1000]/V \quad (5)$$

where c is the standard solution concentration of ammonium ferrous sulfate; V_0 is the initial volume of ammonium ferrous sulfate standard solution; V_1 is the water sample titration volume of ammonium ferrous sulfate standard solution; V represents water sample volume.

2.5. Statistical Analysis

Statistical analyses in particulate organic matters, Chl-a, and water quality factors were performed using SPSS 16.0 software (SPSS Inc., Chicago, IL, USA). Data over the three replicate drums in the short-term experiment were expressed as the arithmetic mean ± standard deviation (SD) and analyzed by one-way ANOVA. The paired differences between treatments were determined by LSD-test, where p values less than 0.05 were accepted as a significant difference and expressed with a different letter in tables and figures. Each data in the long-term experiment was represented the average value basing on the same season, including Spring (21 March, 18 April, 28 May), Summer (20 June, 19 July, 12 August), Autumn (4 September, 11 October), and Winter (25 December, 15 January). The paired results of tailwater discharge area, *H. cumingii* purification area, and ecological purification area were grouped for preliminary comparison of water purification effect in four seasons.

3. Results

3.1. Short-Term Effects of H. cumingii on TSS, FA, and POC

Purification effects of *H. cumingii* on the particulate organic matter are presented in Table 1. The results show that TSS, FA, and POC in the control group reached 50.33 ± 6.08 mg L^{-1}, 16.60 ± 0.04 mg L^{-1}, and 10.72 ± 0.03 mg L^{-1}, respectively. The results also reveal that *H. cumingii* individuals could significantly reduce TSS, FA, and POC ($p < 0.05$). Among them, 12 individuals (G4) of *H. cumingii* could significantly reduce TSS compared to the treatment without mussel (CG), with its percentage of filtering effect reaching 39.06%. Although density-dependent reductions were observed in the G1, G2, and G3 groups, they were not significantly different from the control group ($p > 0.05$). Although FA concentration in G1 significantly higher than that in CG, *H. cumingii* significantly reduced that in G2, G3, and G4 groups, with the highest filtration effect appeared in G4 ($p < 0.05$). Moreover, compared to CG, the concentration of POC was significantly dropped ($p < 0.05$) in groups in all treatments with mussel, and the filtering effect of *H. cumingii* was from 55.2% to 60.0%.

Table 1. Total suspended solids (TSS), fatty acid (FA), and particulate organic carbon (POC) in different mussel density treatments.

	CG	G1	G2	G3	G4
TSS (mg L^{-1})	50.33 ± 6.08 ^{a}	46.33 ± 7.81 ^{a}	40.67 ± 2.52 ^{ab}	39.00 ± 10.26 ^{ab}	30.67 ± 3.79 ^{b}
FA (mg L^{-1})	16.6 ± 0.04 ^{a}	17.31 ± 0.02 ^{b}	12.38 ± 0.25 ^{c}	12.22 ± 0.19 ^{c}	10.48 ± 0.04 ^{d}
POC (mg L^{-1})	10.72 ± 0.03 ^{a}	4.80 ± 0.13 ^{b}	4.29 ± 0.12 ^{d}	4.41 ± 0.11 ^{c}	4.73 ± 0.23 ^{b}

Note: CG, G1, G2, G3 and G4 represent 0 mussels, 3 mussels, 6 mussels, 9 mussels and 6 mussels, respectively. Different lowercase letters denote significant difference between different treatments ($p < 0.05$).

Overall, *H. cumingii* showed excellent filtration effects on TSS, FA, and POC in pond water, and its effects were associated with its density.

3.2. Filtering Effect of H. cumingii on Phytoplankton

Short-term effects of *H. cumingii* on Chl-a and PB were represented in Figure 2. Among them, the concentration of Chl-a in CG reached 9.97 μg L^{-1}. The concentration of Chl-a in treatment groups from G1 to G4 was significantly lower than that of the control group labeled as CG. However, there was no significant difference between the treatment groups, with a percentage of filtering effect from 45.2% to 61.1% (Figure 2A).

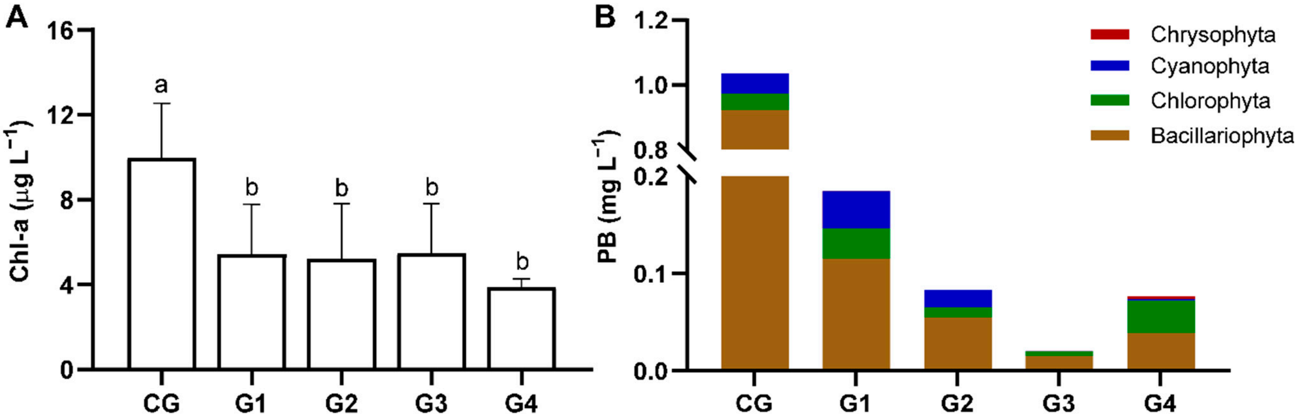

Figure 2. Chlorophyll-a (**A**) and phytoplankton biomass (PB) (**B**) in different mussel density treatments. Note: CG, G1, G2, G3 and G4 represent 0 mussels, 3 mussels, 6 mussels, 9 mussels and 6 mussels, respectively. Different lowercase letters denote significant difference between different treatments ($p < 0.05$).

A total of 29 species of planktonic algae belonging to Cyanophyta (4 species), Chlorophyta (14 species), Bacillariophyta (10 species), and Chrysophyta (1 species) were found in this study. However, *Mallomonas candata* Iwan belonging to the Chrysophyta was only found in G4 (Figure 2B). In detail, the PB in CG reached 1.04 mg L^{-1} and the proportions of Bacillariophyta, Chlorophyta, and Cyanophyta in the control group were 89.3%, 4.4%, and 6.3%, respectively.

The short-term experiment results indicated that *H. cumingii* individuals could effectively reduce the total PB in all treatment groups with mussel, and this downward trend of the total PB was consistent with the detection results of Chl-a. The total biomass of Bacillariophyta, Chlorophyta, and Cyanophyta was decreased to different degrees in all treatment groups. Moreover, phytoplankton community characteristics, including species number, density, and diversity index were shown in Table 2. In the control group, the biomass of nine kinds of plankton algae was more than 0.01 mg L^{-1}, including *Navicula simplex* Krassk (37.4%), *Synedra acus* Kützing (23.2%), *Synedra ulna* Ehrenberg (10.1%), *Diatoma elongatum* Ag (8.1%), *Melosira granulata* Ralfs (6.5%), *Navicula cincta* Van Heurck (2.6%), *Gonium sociale* (2.7%), *Nostoc communes* Vauch (4.3%) and *Chroococcus minor* Näg (1.6%). Moreover, the number of observed phytoplankton species in all treatment groups was 22 (CG), 17(G1), 15(G2) 11(G3) and 16(G4). The density of phytoplankton was dropped sharply from 12 × 10^5 cell L^{-1} to a range from 5.53 to 1.72, respectively, with its alteration trend being consistent with the detection results of Chl-a and PB. For the diversity of phytoplankton, the Shannon-Wiener index in G3 and G4 groups were lower than that of CG, G1, and G2 groups. In the long-term experiment, PB was greater than 25 mg L^{-1} in spring, Summer and Autumn.

Table 2. Phytoplankton community characteristics in different treatments.

Phytoplankton Statistical Analysis	CG	G1	G2	G3	G4
Bacillariophyta Biomass (10^{-3} mg L^{-1})	922.20	115.66	55.04	15.15	39.30
Navicula simplex Krassk	386.43	17.97	10.48	5.99	1.50
Synedra acus Kützing	239.65	31.95	17.97	5.99	17.97
Synedra ulna Ehrenberg	103.85	10.65			3.99
Diatoma elongatum Ag.	83.88	2.66	4.99	1.00	3.00
Melosira granulata Ralfs	67.10	51.12	20.77		10.38
Navicula cincta Van Heurck	27.26	1.30	0.65		1.95
Cocconeis placentula Hust	4.99				
Cyclotella meneghiniana Kütz	3.99			2.00	
Stauroneis kriegeri Patrick	3.06		0.17	0.17	0.51
Gomphonema constrictum Grunow	2.00				
Chlorophyta Biomass (10^{-3} mg L^{-1})	45.63	30.49	10.28	4.94	36.43
Gonium sociale	27.56	14.38	5.99	3.00	27.56
Planktosphaeria gelatinosa Smith	4.49	6.66	1.65		
Crucigenia puadrata Morren	3.99	3.20	1.20		
Sceaedesmus cavinaus Chod	3.20	2.66	0.85		0.80
Crucigenia tetrapedia Morr	2.40	1.07	0.40	1.20	
Schroederia spiralis Korsch	2.00				
Selenastrum gracile	1.20	1.33			0.60
Ankistrodesmus angustus B.S. Korš	0.40	0.27	0.20	0.20	0.20
Cosmarium subtumidum Nordst	0.40				
Sceaedesmus oblipuus Kütz					0.80
Sceaedesmus dimorphus Kütz		0.93		0.55	
Pediastrum tetras Ralfs					1.60
Pediastrum duplex Mey					1.60
Cyanophyta Biomass (10^{-3} mg L^{-1})	64.44	38.30	17.77	0.53	1.64
Nostoc communes Vauch	43.94	13.31	15.98		
Chroococcus minor Näg	16.11	3.15	0.59	0.15	1.63
Phormidium tenue Gom	4.39	21.83	1.20		
Merismopedia punctata Meyen				0.38	0.01
Species number	22	17	15	11	16
Total Biomass (10^{-3} mg L^{-1})	1032.27	184.45	83.09	20.62	77.09
Phytoplankton Density	12.00	5.53	3.06	1.72	2.01
Diversity index H’	3.61	3.23	3.35	1.49	2.85

In general, the number of species, biomass, and diversity index of phytoplankton could be reduced effectively by the filtering effects of *H. cumingii*.

3.3. Effect of H. cumingii on the Water Conditions

Short-term effects of *H. cumingii* individuals on the EC, COD, TN, and TP were given in Figures 3 and 4.

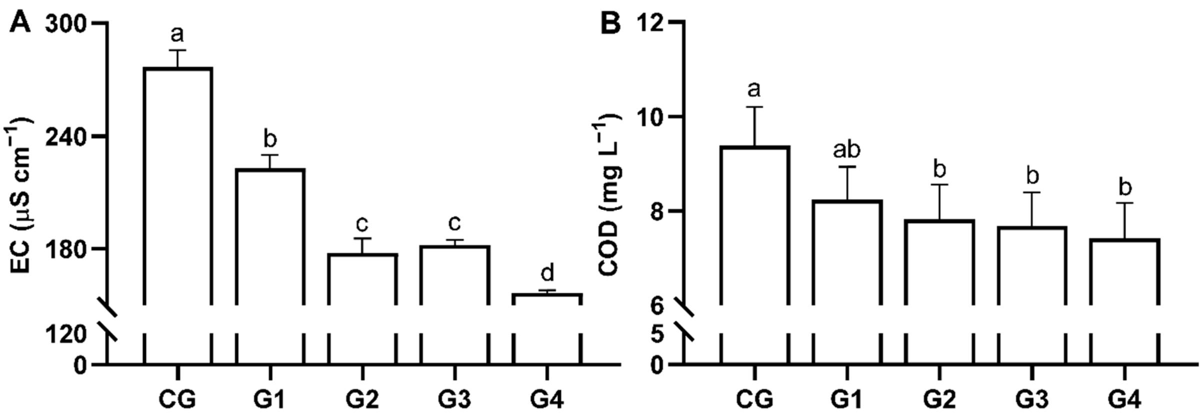

Figure 3. Electric conductivity (**A**) and chemical oxygen demand (COD) (**B**) in different mussel density treatments. Note: CG, G1, G2, G3 and G4 represent 0 mussels, 3 mussels, 6 mussels, 9 mussels and 6 mussels, respectively. Different lowercase letters denote significant difference between different treatments ($p < 0.05$).

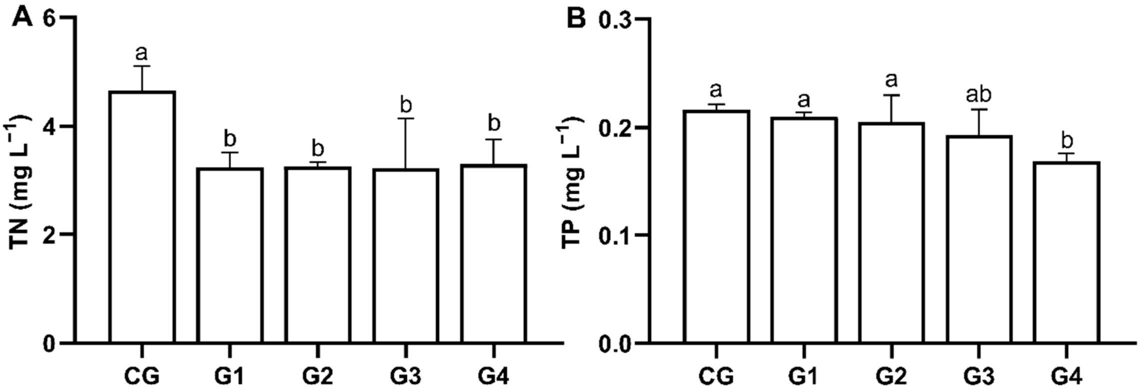

Figure 4. Total nitrogen (TN) (**A**) and total phosphorus (TP) (**B**) in different mussel density treatments. Note: CG, G1, G2, G3 and G4 represent 0 mussels, 3 mussels, 6 mussels, 9 mussels and 6 mussels, respectively. Different lowercase letters denote significant difference between different treatments ($p < 0.05$).

In detail, the EC showed a significant reduction ($p < 0.05$) in all treatment groups from G1 to G4 and its variation tendency showed a typical density-dependent effect in the whole experimental period (Figure 3A). Our results also revealed that at least six individuals (G2) of *H. cumingii* could significantly reduce ($p < 0.05$) the COD values compared to the treatment without mussel (CG) (Figure 3B) and a similar effect was found in TN content (Figure 4A). For TP content, however, it only showed a significant decrease ($p < 0.05$) in the treatments with at least 12 individuals (G4) of *H. cumingii* (Figure 4B).

The results indicated that *H. cumingii* individuals were able to reduce the EC, COD, TN, and TP of water.

3.4. Annual Survey Results in the Recirculating Aquaculture Pond

In the long-term experiment, the annual variations in temperature and pH of recirculating aquaculture water were shown in Figure 5A. Among them, the average water temperature in autumn reached 29.7 °C, and in winter, that was as low as 14.2 °C. Moreover, it in all seasons exceeded 20 °C except for winter. The water quality of the pond was weakly alkaline throughout the year. Thus, the results showed that *H. cumingii* individuals adapted to the year-round changes of pH and temperature in the recirculating aquaculture pond.

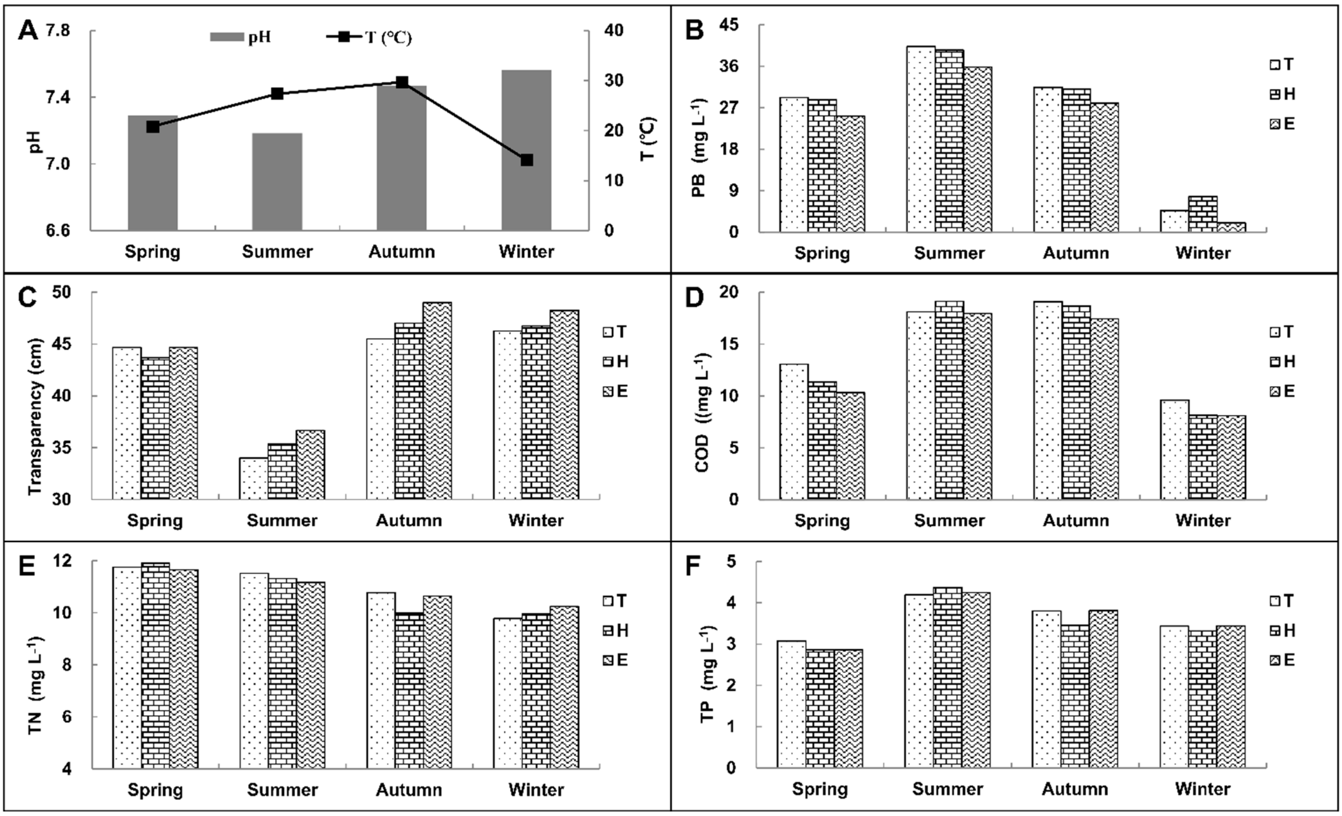

Figure 5. Mean seasonal variations in typical properties of temperature and pH (**A**), purifying effects of *H. cumingii* on PB (**B**), transparency (**C**), COD (**D**), TN (**E**), and TP (**F**) in the recirculating aquaculture pond. Where the letter "T" represents the tailwater discharge area, "H" represents the *H. cumingii* purification area and "E" represents the ecological purification area.

The purifying effects of *H. cumingii* individuals on the PB, transparency, COD, TN, and TP were reflected in Figure 5B–F. The same as the variation trend of water temperature, PB remained above 20 mg L^{-1} from spring to autumn. *H. cumingii* individuals showed a potential filtering effect on phytoplankton based on visual interpretation of Figure 5B, as the PB in the ecological purification area was lower than that in the tailwater discharge area. On the other hand, due to their filtering effects on phytoplankton and particulate organic matter, the transparency of the ecological purification area was higher than that of other areas based on visual interpretation of Figure 5C. Identical to the PB, the COD value of the ecological purification area in each quarter was reduced compared with that in other areas, which was consistent with the short-term experiment results (Figure 5D). However, different from the short-term experiment, *H. cumingii* individuals did not reduce the TN and TP concentration, but increased in autumn and winter (Figure 5E,F).

4. Discussion

Since the beginning of artificial propagation in the middle of the 1980s, *H. cumingii* has become a dominant species of cultivating pearl in freshwater and is mainly distributed in China's mid-east regions. However, only a few studies are involved in proper growth and pearl cultivation of *H. cumingii* [34]. Our newly approved Chinese Shellfish System Chongqing Comprehensive Experimental Station (2018), as the unique freshwater comprehensive experimental station in the non-main producing areas, is mainly responsible for exploring the ecological service function and fishery economic value of freshwater shellfish. Moreover, this study can further develop the shellfish industry based on the recirculating aquaculture model.

In the present study, *H. cumingii* individuals could effectively reduce TSS, POC, and FA in the aquaculture pond, with average percentage of filtering effect respectively reaching 22.19%, 57.48%, and 21.00% in the high-density group. The effects of *H. cumingii* was typically density-dependent on TSS, FA, and POC. The results indicated that *H. cumingii* profoundly regulated the substance cycle by direct filtration for suspended particulate organic matter in water.

Autochthonous particulate organic matter sources, such as phytoplankton, contained a higher percentage of labile organic composition than allochthonous sources, making it be as an appropriate proper source for primary consumers [35,36]. The organic carbon is also derived from allochthonous and autochthonous sources, including particulate and dissolved forms, and irradiation could realize the transformation of dissolved organic carbon to organic carbon particles [37,38]. Moreover, fatty acid directly or indirectly from primary producers, such as phytoplankton and photosynthetic bacteria, was an important evaluation index of primary water productivity [39]. However, the superfluous particulate organic matter could result in the deterioration of water quality and water eutrophication in the exoteric river estuary and enclosed pond water system [40]. Therefore, the effective reduction in particulate organic matter may be attributed to the direct filtration of *H. cumingii* for phytoplankton and organic debris.

Further research indicated that *H. cumingii* could effectively control the biomass of diatoms, green algae, and cyanobacteria, the primary food sources of bivalve shellfish. Especially in the control of the nine kinds of plankton algae with their concentration being more than 0.01 mg L^{-1}, they were *Navicula simplex* Krassk, *Synedra acus* Kützing, *Synedra ulna* Ehrenberg, *Diatoma elongatum* Ag, *Melosira granulata* Ralfs, *Navicula cincta* Van Heurck, *Gonium sociale*, *Nostoc communes* Vauch and *Chroococcus minor* Näg. Among them, six species of plankton diatoms made up 87.9% of PB in the pond water. Furthermore, *H. cumingii* filtered 87.3 percent of the six species of plankton diatoms. Briefly, *H. cumingii* showed a powerful filtering function on phytoplankton as its resulting filtration rates were greater than 82% in all treatment groups from G1 to G4, and this downward trend was consistent with the detected values of Chl-a. Therefore, the use of *H. cumingii* has been proposed as an alternative way to control algal bloom in eutrophic water in recent years [19].

As an essential indicator of the PB, Chl-a has been often used to evaluate water quality [41]. Studies had revealed that the filter-feeding *H. cumingii* may indirectly promote submerged macrophyte growth by controlling the density of algal bloom [20]. However, this study confirmed that *H. cumingii* considered as the primary consumer could effectively filter phytoplankton and was of great significance to nutrient utilization and the control of algae blooms in aquaculture.

Annual monitoring results show that transparency in the ecological purification area was higher than that in the tailwater discharge area due to the effect of *H. cumingii* on phytoplankton and particulate organic matter in the recirculating aquaculture pond. The other results show that co-cultivation of an aquatic plant (*Ipomoea aquatica*) and aquatic animal (*H. cumingii*) could effectively enhance the removal rates of the pollutant from the ecological floating bed contained with artificial medium [42]. These results also pointed out that the filter-feeding *H. cumingii* promoted the solubilization and mineralization of particulate organic matters, and enhanced the purification efficiency from the ecological floating bed by purifying microorganisms [42]. In eutrophic water, phytoplankton using N and P as nutrient sources generally grows rapidly and easily, resulting in algal bloom [43]. The concentration of TP from treatment groups in the short-term experiment showed a decreasing trend with the increase in mussel density. However, in the long-term experiment, *H. cumingii* individuals did not reduce the TN and TP concentration, but increased in autumn and winter. This result may be caused by climate change and weakened body functions. In general, this study revealed the potential role of *H. cumingii* in water purification, including increasing the transparency of water and reducing the EC and COD.

5. Conclusions

The overall water purification mechanism of *H. cumingii* remains uncertain, but current results have indicated that *H. cumingii* is an excellent way for the filtration of particulate organic matter, the control of algal bloom, and the regulation of water quality in aquaculture. Results from the short-term experiment and long-term monitoring experiment indicated that the model of culturing *H. cumingii* based on recirculating aquaculture system is of great significance in the ecological purification and healthy aquaculture. As potential sink of CO_2, *H. cumingii* furtherly may contribute to the reduction in greenhouse gases. In summary, this study provides a feasible basis for us to carry out the ecological cultivation and application of *H. cumingii* in the southwest of China in the future.

Author Contributions: Conceptualization, X.Y. and Q.Y.; methodology, X.Y.; software, Q.Y.; validation, X.Y., Q.Y. and Z.Z.; investigation, Z.Z. and B.X.; data curation, X.T.; writing-original draft preparation, X.Y.; writing-review and editing, Q.Y.; supervision, Z.W.; project administration, S.S. and W.Y.; funding acquisition, W.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Chongqing Natural Science Foundation Project (Grant No. cstc2020jcyj-msxmX0971), Chongqing Municipal Social Livelihood Project (Grant No. cstc2018jscx-msybX0235), and China Agriculture Research System (Grant No. CARS-49).

Institutional Review Board Statement: The protocol for this study does not need an ethical approval.

Informed Consent Statement: Not applicable for studies not involving humans.

Data Availability Statement: Research data are not shared.

Conflicts of Interest: All of the authors declare that they have no conflicts of interest.

References

1. Cao, L.; Wang, W.; Yang, Y.; Yang, C.; Yuan, Z.; Xiong, S.; Diana, J. Environmental impact of aquaculture and countermeasures to aquaculture pollution in China. *Environ. Sci. Pollut. Res.* **2007**, *14*, 452–462, doi:10.1065/espr2007.05.426.
2. Horton, M.; Keys, A.; Kirkwood, L.; Mitchell, F.; Kyle, R.; Roberts, D. Sustainable catchment restoration for reintroduction of captive bred freshwater pearl mussels *Margaritifera margaritifera*. *Limnologica* **2015**, *50*, 21–28, doi:10.1016/j.limno.2014.11.003.
3. Kingsford, R.T.; Biggs, H.C.; Pollard, S.R. Strategic adaptive management in freshwater protected areas and their rivers. *Biol. Conserv.* **2011**, *144*, 1194–1203, doi:10.1016/j.biocon.2010.09.022.
4. Zhang, X.; Xiao, F.; Li, S.; Liu, X.; Han, X.; Jiang, K.; Hu, H. *China Fishery Statistical Yearbook 2018*; China Agriculture Press: Beijing, China, 2018.
5. Zhang, B.; Cao, C.; Gu, J.; Liu, T. A new environmental protection law, many old problems? Challenges to environmental governance in China. *J. Environ. Law* **2016**, *28*, 325–335, doi:10.1093/jel/eqw014.
6. Wang, L.; He, F.; Sun, J.; Hu, Y.; Huang, T.; Zhang, Y.; Wu, Z. Effects of three biological control approaches and their combination on the restoration of eutrophicated waterbodies. *Limnology* **2017**, *18*, 301–313, doi:10.1007/s10201-016-0507-6.
7. Wang, L.; Ma, L.; Sun, J.; Zhang, Y.; Zhou, Q.; Wu, Z.; He, F. Effects of different aquaculture methods for introduced bivalves (*Hyriopsis cumingii*) on seston removal and phosphorus balance at the water-sediment interface. *J. Freshw. Ecol.* **2018**, *33*, 251–265, doi:10.1080/02705060.2018.1429328.
8. Jeppesen, E.; Sondergaard, M.; Lauridsen, T.L.; Davidson, T.A.; Liu, Z.; Mazzeo, N.; Meerhoff, M. Biomanipulation as a restoration tool to combat eutrophication: Recent advances and future challenges. *Adv. Ecol. Res.* **2012**, *47*, 411–488, doi:10.1016/B978-0-12-398315-2.00006-5.
9. Vaughn, C.C.; Hakenkamp, C.C. The functional role of burrowing bivalves in freshwater ecosystems. *Freshw. Biol.* **2001**, *46*, 1431–1446, doi:10.1046/j.1365-2427.2001.00771.x.
10. Enriquez-Ocana, L.F.; Nieves-Soto, M.; Pina-Valdez, P.; Martinez-Cordova, L.R.; Medina-Jasso, M.A. Evaluation of the combined effect of temperature and salinity on the filtration, clearance rate and assimilation efficiency of the mangrove oyster *Crassostrea corteziensis*. *Arch. Biol. Sci.* **2012**, *64*, 479–488, doi:10.2298/abs1202479o.
11. Jones HF, E.; Pilditch, C.A.; Bryan, K.R.; Hamilton, D.P. Effects of infaunal bivalve density and flow speed on clearance rates and near-bed hydrodynamics. *J. Exp. Mar. Biol. Ecol.* **2011**, *401*, 20–28, doi:10.1016/j.jembe.2011.03.006.
12. Tokumon, R.; Cataldo, D.; Boltovskoy, D. Effects of suspended inorganic matter on filtration and grazing rates of the invasive mussel *Limnoperna fortunei* (Bivalvia: *Mytiloidea*). *J. Molluscan Stud.* **2016**, *82*, 201–204, doi:10.1093/mollus/eyv024.

13. Olden, J.D.; Ray, L.; Mims, M.C.; Horner-Devine, M.C. Filtration rates of the non-native Chinese mystery snail (*Bellamya chinensis*) and potential impacts on microbial communities. *Limnetica* **2013**, *32*, 107–120, doi:10.23818/limn.32.11.
14. Ismail, N.S.; Tommerdahl, J.P.; Boehm, A.B.; Luthy, R.G. Escherichia coli reduction by bivalves in an impaired river impacted by agricultural land use. *Environ. Sci. Technol.* **2016**, *50*, 11025–11033, doi:10.1021/acs.est.6b03043.
15. Bai, Z.Y.; Han, X.K.; Liu, X.J.; Li, Q.Q.; Li, J.L. Construction of a high-density genetic map and QTL mapping for pearl quality-related traits in *Hyriopsis cumingii*. *Sci. Rep.* **2016**, *6*, 32608, doi:10.1038/srep32608.
16. Zhao, Y.; Bai, Z.; Fu, L.; Liu, Y.; Wang, G.; Li, J. Comparison of growth and pearl production in males and females of the freshwater mussel, *Hyriopsis cumingii*, in China. *Aquac. Int.* **2013**, *21*, 1301–1310, doi:10.1007/s10499-013-9632-y.
17. Sorokin, I.I.; Giovanardi, O.; Pranovi, F.; Sorokin, P.I. Need for restricting bivalve culture in the southern basin of the Lagoon of Venice. *Hydrobiologia* **1999**, *400*, 141–148, doi:10.1023/a:1003707231839.
18. Gallardi, D. Effects of bivalve aquaculture on the environment and their possible mitigation: A review. *Fish. Aquac. J.* **2014**, *5*, doi:10.4172/2150-3508.1000105.
19. Liu, Q.; Hu, M.; Wu, Z. Can mussels change phytoplankton community structure and enhance prawn production in semi-enclosed prawn ponds? *Aquac. Res.* **2015**, *46*, 2559–2564, doi:10.1111/are.12394.
20. He, H.; Liu, X.; Liu, X.; Yu, J.; Li, K.; Guan, B.; Jeppesen, E.; Liu, Z. Effects of cyanobacterial blooms on submerged macrophytes alleviated by the native Chinese bivalve *Hyriopsis cumingii*: A mesocosm experiment study. *Ecol. Eng.* **2014**, *71*, 363–367, doi:10.1016/j.ecoleng.2014.07.015.
21. Zhao, L.; Walliser, E.O.; Mertz-Kraus, R.; Schoene, B.R. Unionid shells (*Hyriopsis cumingii*) record manganese cycling at the sediment-water interface in a shallow eutrophic lake in China (Lake Taihu). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2017**, *484*, 97–108, doi:10.1016/j.palaeo.2017.03.010.
22. Liu, J.; Yan, H.; Liao, Z.; Zhang, K.; Schmidt, A.R.; Tao, T. Laboratory analysis on the surface runoff pollution reduction performance of permeable pavements. *Sci. Total Environ.* **2019**, *691*, 1–8, doi:10.1016/j.scitotenv.2019.07.028.
23. Zhang, J.; Liu, G.; Wang, R.; Huang, H. Polycyclic aromatic hydrocarbons in the water-SPM-sediment system from the middle reaches of Huai River, China: Distribution, partitioning, origin tracing and ecological risk assessment. *Environ. Pollut.* **2017**, *230*, 61–71, doi:10.1016/j.envpol.2017.06.012.
24. Weng, J.Z.; Xu, H.S. *The Common Freshwater Phytoplankton Algae atlas of China*; Shanghai Science and Technology Press: Shanghai, China, 2010; pp. 1–225.
25. Zhou, X.; Zheng, J. *Hydrobiology Atlas of Chongqing Section of the Three Gorges Reservoir Area*; China Environmental Science Press: Beijing, China, 2005; pp. 1–125.
26. Yu, X.B.; Hao, K.; Ling, F.; Wang, G.X. Aquatic environmental safety assessment and inhibition mechanism of chemicals for targeting *Microcystis aeruginosa*. *Ecotoxicology* **2014**, *23*, 1638–1647, doi:10.1007/s10646-014-1303-x.
27. Zhang, Y.; Dong, J.; Ling, J.; Wang, Y.; Zhang, S. Phytoplankton distribution and their relationship to environmental variables in Sanya Bay, South China Sea. *Sci. Mar.* **2010**, *74*, 783–792, doi:10.3989/scimar.2010.74n4783.
28. Wei, Y.; Sun, J.; Zhang, X.; Wang, J.; Huang, K. Picophytoplankton size and biomass around equatorial eastern Indian Ocean. *MicrobiologyOpen* **2019**, *8*, e00629, doi:10.1002/mbo3.629.
29. Spatharis, S.; Roelke, D.L.; Dimitrakopoulos, P.G.; Kokkoris, G.D. Analyzing the (mis) behavior of Shannon index in eutrophication studies using field and simulated phytoplankton assemblages. *Ecol. Indic.* **2011**, *11*, 697–703, doi:10.1016/j.ecolind.2010.09.009.
30. Wei, F.S.; Qi, W.Q.; Bi, T.; Sun, Z.; Huang, Y. *The Standard Methods of Water and Wastewater Monitoring and Analysis of China*; China Environmental Science Press: Beijing, China, 2002.
31. Chen, G.M. Ammonium molybdate spectrophotometric method for determination of total phosphorus in municipal sewage sludge. *China Water Wastewater* **2006**, *22*, 85–86.
32. Meng, X.; Zhu, C.; Chen, X. Alkaline potassium persulfate UV spectrophotometric determination of total nitrogen frequently asked questions and solutions. *Environ. Sci. Manag.* **2010**, *35*, 126–128.
33. Dedkov, Y.M.; Elizarova, O.V.; Kelina, S.Y. Dichromate method for the determination of chemical oxygen demand. *J. Anal. Chem.* **2000**, *55*, 777–781, doi:10.1007/bf02757915.
34. Yan, L.L.; Zhang, G.F.; Liu, Q.G.; Li, J.L. Optimization of culturing the freshwater pearl mussels, *Hyriopsis cumingii* with filter feeding Chinese carps (bighead carp and silver carp) by orthogonal array design. *Aquaculture* **2009**, *292*, 60–66, doi:10.1016/j.aquaculture.2009.03.037.
35. Canuel, E.A. Relations between river flow, primary production and fatty acid composition of particulate organic matter in San Francisco and Chesapeake Bays: A multivariate approach. *Org. Geochem.* **2001**, *32*, 563–583, doi:10.1016/s0146-6380(00)00195-9.
36. Volkman, J.K.; Revill, A.T.; Holdsworth, D.G.; Fredericks, D. Organic matter sources in an enclosed coastal inlet assessed using lipid biomarkers and stable isotopes. *Org. Geochem.* **2008**, *39*, 689–710, doi:10.1016/j.orggeochem.2008.02.014.
37. Bauer, J.E.; Cai, W.-J.; Raymond, P.A.; Bianchi, T.S.; Hopkinson, C.S.; Regnier, P.A.G. The changing carbon cycle of the coastal ocean. *Nature* **2013**, *504*, 61–70, doi:10.1038/nature12857.
38. Porcal, P.; Dillon, P.J.; Molot, L.A. Photochemical production and decomposition of particulate organic carbon in a freshwater stream. *Aquat. Sci.* **2013**, *75*, 469–482, doi:10.1007/s00027-013-0293-8.
39. Gladyshev, M.I.; Sushchik, N.N.; Anishchenko, O.V.; Makhutova, O.N.; Kolmakov, V.I.; Kalachova, G.S.; Kolmakova, A.A.; Dubovskaya, O.P. Efficiency of transfer of essential polyunsaturated fatty acids versus organic carbon from producers to consumers in a eutrophic reservoir. *Oecologia* **2011**, *165*, 521–531. doi:10.1007/s00442-010-1843-6.

40. Zhang, L.; Yin, K.; Wang, L.; Chen, F.; Zhang, D.; Yang, Y. The sources and accumulation rate of sedimentary organic matter in the Pearl River Estuary and adjacent coastal area, Southern China. *Estuar. Coast. Shelf Sci.* **2009**, *85*, 190–196, doi:10.1016/j.ecss.2009.07.035.
41. Boyer, J.N.; Kelble, C.R.; Ortner, P.B.; Rudnick, D.T. Phytoplankton bloom status: Chlorophyll a biomass as an indicator of water quality condition in the southern estuaries of Florida, USA. *Ecol. Indic.* **2009**, *9*, S56–S67, doi:10.1016/j.ecolind.2008.11.013.
42. Wang, G.; Wang, X.; Wu, L.; Li, X. Contribution and purification mechanism of bio components to pollutants removal in an integrated ecological floating bed. *J. Civ. Archit. Environ. Eng.* **2015**, *4*, 136–141.
43. Xu, H.; Paerl, H.W.; Qin, B.; Zhu, G.; Gao, G. Nitrogen and phosphorus inputs control phytoplankton growth in eutrophic Lake Taihu, *China*. *Limnol. Oceanogr.* **2010**, *55*, 420–432, doi:10.4319/lo.2010.55.1.0420.