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Removal of Nitrogen and Phosphorus in Low Polluted Wastewater by Aquatic Plants: Impact of Monochromatic Light Radiation

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Abstract: Plant absorption via aquatic plants is vital for the deep purification of treated wastewater. This study aimed to determine the removal efficiencies of nitrogen and phosphorus for different aquatic plants and the effect of monochromatic light as compared to white light. Five plants (i.e., *Iris pseudacorus*, *Oenanthe javanica*, *Zantedeschia aethiopica*, *Ipomoea aquatica Forssk.* and *Sagittaria trifolia*) were cultured in prepared wastewater and radiated by white, red, green and blue LED lamps with 8 h radiation per day, respectively. After 4 d of cultivation, the *O. javanica* and *S. trifolia* exhibited relatively better growth status and higher TP removal rates (90%). The blue light radiation played a key role in the TP uptake of the tested plants. The N removal rates of plants were relatively lower (10–40%), limited by the low COD content. The *S. trifolia* exhibited the highest efficiency, and red light promoted the removal of TN and NO_3^--N, whereas NH_4^+-N removal was driven by blue light radiation. So, *O. javanica* and *S. trifolia* coupled with blue and red lamps as supplementary light were suggested for the deep purification of municipal treated wastewater. The effect of intensity and ratio of monochromatic lights could be a direction for further research.

Keywords: aquatic plant; removal rate; three primary colors; light radiation; treated water reuse

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1. Introduction

Municipal wastewater continuously places a huge burden on the natural environment [1,2], which directly affects environmental quality and ecological equilibrium [3,4]. To reduce this impact, municipal wastewater needs purification treatment before releasing it to natural waters [5]. However, the purified wastewater still contains certain amounts of pollutants, which needs further treatment to reduce the impact to the natural environment. According to the discharge standard of pollutants for municipal wastewater treatment plants (GB 18918-2002) [6] and the environmental quality standard of surface water (GB 3838-2002) [7], the pollutant content for the class I standard of municipal wastewater treatment plant effluents is still higher than the class V standard for natural surface water. In general, the pollutants in tailwater are treated by tailwater constructed wetland (CW), which is characterized as low-cost and high-efficiency [8]. As an important part of CW, the plants play significant roles in the removal efficacy of pollutants and the cycle of elements for nitrogen and phosphorus [9,10]. Thus, it is of great significance to screen plants with high removal efficacy and economic value and to study the growth status of plants with relatively low-nutrient solutions.

The removal efficacy of nitrogen and phosphorus is dependent on the plant species, and the initial nutrient contents also influence the removal rates [11,12]. Then, the selection

of plant species is essential to the removal efficiency under relatively low-nutrient content solutions. *Iris pseudacorus* is one of the most common plants used in CW. This plant has the characteristic of strong adaptability [13] and can be used as a source of plant dyestuff [14]. *Zantedeschia aethiopica* (L.) Spreng. and *Sagittaria trifolia* var. *sinensis Sims* tuberous plants are widely used in CW [15–17]. Due to the high requirement of phosphorus for the growth of tubers, these plants can be utilized as dominant plants to remove phosphorus in CW [18,19]. *Oenanthe javanica* and *Ipomoea aquatica Forssk.* are common floating plants which can be used in the CW [20,21]. These kinds of plants are characterized by rapid growth, strong vitality and a long vegetative growth stage, which poses a great need for nitrogen for these plants [22,23]. The above five common plants have the advantage of strong adaptive capacity to the growing environment, which allows them to easily acclimatize themselves to the relatively low-nutrient content environment.

Light radiation is one of the indispensable elements for the growth of plants [24,25]. It has been proven that the growth of *Lippia alba* (*L. alba*, Verbenaceae) was significantly influenced by light quality; blue/red lamps induced greater fresh weight and a higher photosynthetic pigment level for *L. alba* as compared to white LED lamps [24]. The signaling pathways for the growth and defense of plants are linked to light spectral composition [26]. It has been reported that increase in blue light radiation promotes photosynthesis and leaf thickness in cucumber [27] and increases the content of chlorophylls and carotenoids in parsley, mustard and beet [28]. Increase in far-red radiation can significantly increase tomato fruit production by affecting the dry mass partitioning pattern [29]. Red light radiation is the most efficient for hydrocarbon production of *Botryococcus braunii* [30]. For green light, high-intensity green light is effective at promoting the photosynthetic rate and growth of lettuce plants (*Lactuca sativa*) [31]. The above instances indicate that the growth status of plants is linked to light radiation with different wavelengths as a result of the removal efficacies of nutrient contents in wastewater being influenced by different light radiation. Thus, it is of great significance to figure out the influence of radiation in the three primary colors on the removal ability of common CW plants, which is beneficial to enhancing the removal efficiencies of nitrogen and phosphorus in wastewater treatment.

The main objectives of this research were to (1) determine the removal ability of nitrogen and phosphorus by different plants in low-nutrient content wastewater, as well as the growth situation of plants; (2) figure out the impact of monochromatic light radiation on removal rates of nitrogen and phosphorus as compared to white light radiation, as well as the growth status of aquatic plants; and (3) elucidate the role of monochromatic light radiation in the removal mechanism of pollutants by plants.

2. Materials and Methods

2.1. Experimental Water Quality Preparation

Potassium hydrogen phthalate (AR, Fuchen Chemical Reagent Co., Ltd, Tianjin, China), potassium dihydrogen phosphate (AR, Rejinte Chemical Reagent Co., Ltd, Tianjin, China), potassium nitrate (AR, Beilian Fine Chemicals Development Co., Ltd, Tianjin, China) and ammonium chloride (AR, Tianda Chemical Reagent Co., Ltd, Tianjin, China) were used to prepare the target solution. According to the class I effluent standard in the discharge standard of pollutants for the municipal wastewater treatment plant (GB 18918-2002) [6], the experiment solution (COD = 50 mg/L, TN = 15 mg/L, NH_4^+-N = 5 mg/L, NO_3^--N = 10 mg/L and TP = 0.5 mg/L) and culture medium (COD = 150 mg/L, TN = 45 mg/L, NH_4^+-N = 15 mg/L, NO_3^--N = 30 mg/L and TP = 1.5 mg/L) were prepared by dissolving the aforementioned chemical reagents with ultrapure water (18 MΩ), which was prepared by the Ulupure UPT-II-10T ultrapure water system (Chengdu, China).

2.2. Experimental Design

Five plants (i.e., *I. pseudacorus*, *O. javanica*, *Z. aethiopica*, *I. aquatica* and *S. trifolia*) in the same growth phase (vegetative stage) were selected for the experiment. The initial

heights of the plants were approximately 30, 20, 25, 15 and 35 cm for *I. pseudacorus*, *O. javanica*, *Z. aethiopica*, *I. aquatica* and *S. trifolia*, respectively. Before the experiments, the plants were washed with ultrapure water and precultured into 3 L plastic containers (each container had 2, 4, 3, 6 and 3 plants of *I. pseudacorus*, *O. javanica*, *Z. aethiopica*, *I. aquatica* and *S. trifolia*, respectively) with 2 L of culture medium (COD = 150 mg/L, TN = 45 mg/L, NH_4^+-N = 15 mg/L, NO_3^--N = 30 mg/L and TP = 1.5 mg/L) for 15 days; the culture medium was renewed every 5 days. Then, the weight of the plants in each container was measured and the culture medium was changed to experimental solution (COD = 50 mg/L, TN = 15 mg/L, NH_4^+-N = 5 mg/L, NO_3^--N = 10 mg/L and TP = 0.5 mg/L). During the pre-culture and experimental processes, the plants were subject to cycled illumination with white, red, blue and green lamp radiation (120 W), respectively, for 8 h light and 16 h dark at room temperature (22–29 °C). The light radiation spectrum for each lamp is shown in Figure 1. The total power of the light sources used in this experiment was 120 W; the lamp spectrum for each kind of lamp (30 cm underneath the light tube) was determined by HP350UVP portable CCD spectroradiometer (Hangzhou LCE intelligent detection instrument Co., Ltd., Hangzhou, China). The water samples were collected at intervals of 4 days to determine the water quality, including determination of COD, TN, TP, NH_4^+-N, NO_2^--N and NO_3^--N by GL-900Q multiple parameter water quality analyzer (Shandong GeLinKaiRei Precise Instrument Co., Ltd., Heze, China), and the simulated wastewater was renewed after sampling. The selected plants were cultured in a costumed cage, which was covered by felt to avoid the influence of sunlight and other lab light sources, and radiated by white, red, blue and green lamps, respectively. The growth situations of plants under different light radiation for each experimental period are shown in Figure 2. The removal rates of endpoints were calculated according to Equation (1). The chlorophyll content and nitrogen content of plants were measured by a TYS-4N Chlorophyll analyzer (Beijing ZhongKeWeiHe Technology Development Co., Ltd., Beijing, China), as well as the weight of the plants in each container. At the same time, a blank control was taken by radiating a prepared solution under different lamps without the plants during the experimental period, and the mentioned water quality indexes were determined. All experiments were conducted in duplicate. The calculation of the wastewater removal rate is shown in Equation (1).

$$R(\%) = \frac{C_0 - C_t}{C_0} \times 100\% \quad (1)$$

where R (%) is the removal rate of COD, TN, TP, NH_4^+-N and NO_3^--N, respectively; C_0 is the initial concentration at the beginning of each experimental period; and C_t is the final concentration at the ending timepoint of each experimental period.

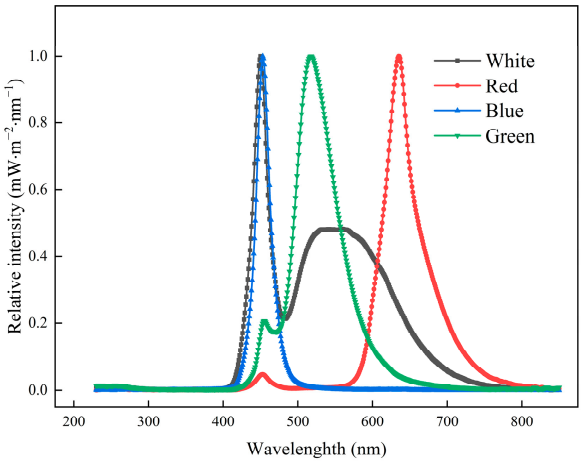

Figure 1. Light radiation spectra of each lamp condition used in this experiment.

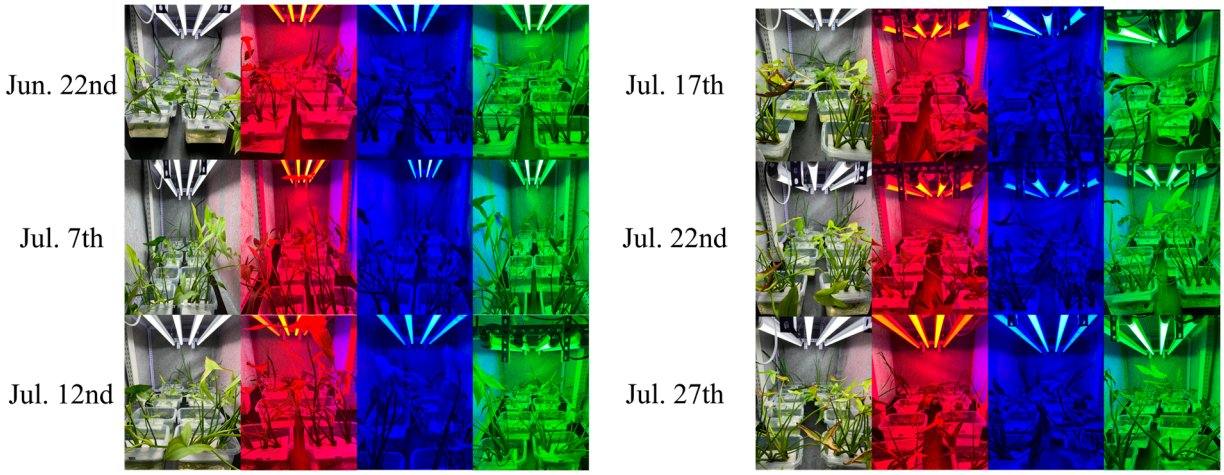

Figure 2. Status of plants under different light radiation for each experimental period.

3. Results

After 4 d of cultivation, the water quality indexes were determined. Due to the target solution being prepared with ultrapure water, the natural variation in the control group was limited due to the lack of microorganisms to convert and assimilate the COD and nitrogen/phosphorus in solution. The change in the water quality indexes was negligible in this case (Figure 3).

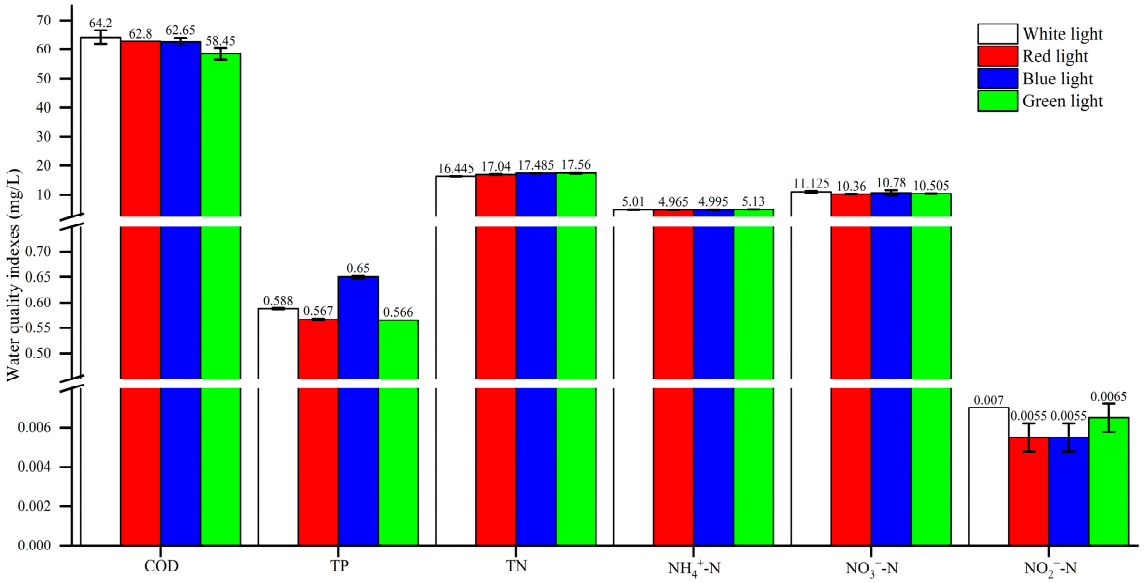

Figure 3. Determination of water quality indexes for blank control.

For COD removal efficiency, all the selected plants showed significant removal capability for COD (Figure 4). The maximum removal rate of COD for the five plants reached more than 95%, which indicated that the rhizosphere microorganisms of the plants were relatively active. The plants had a high absorption capacity for pollutants in wastewater. The order of overall COD removal rates for the five plants was *O. javanica* (85.6%) > *Z. aethiopica* (82.3%) > *S. trifolia* (82.0%) > *I. pseudacorus* (79.4%) > *I. aquatica* (76.7%). The COD removal rates of plants were influenced by different light radiation. For *O. javanica*, *Z. aethiopica* and *I. pseudacorus*, the highest COD removal rates were determined under the radiation of the red lamp. But for *S. trifolia* and *I. aquatica*, the highest mean COD removal rates were determined under white lamp radiation, and relatively smaller removal rates were determined under monochromatic light radiation. The results indicate that COD

removal by plants was influenced by different light radiation, which suggests that the rhizosphere microorganisms were regulated by different monochromatic light radiation and specific microorganisms promoted the COD removal [32].

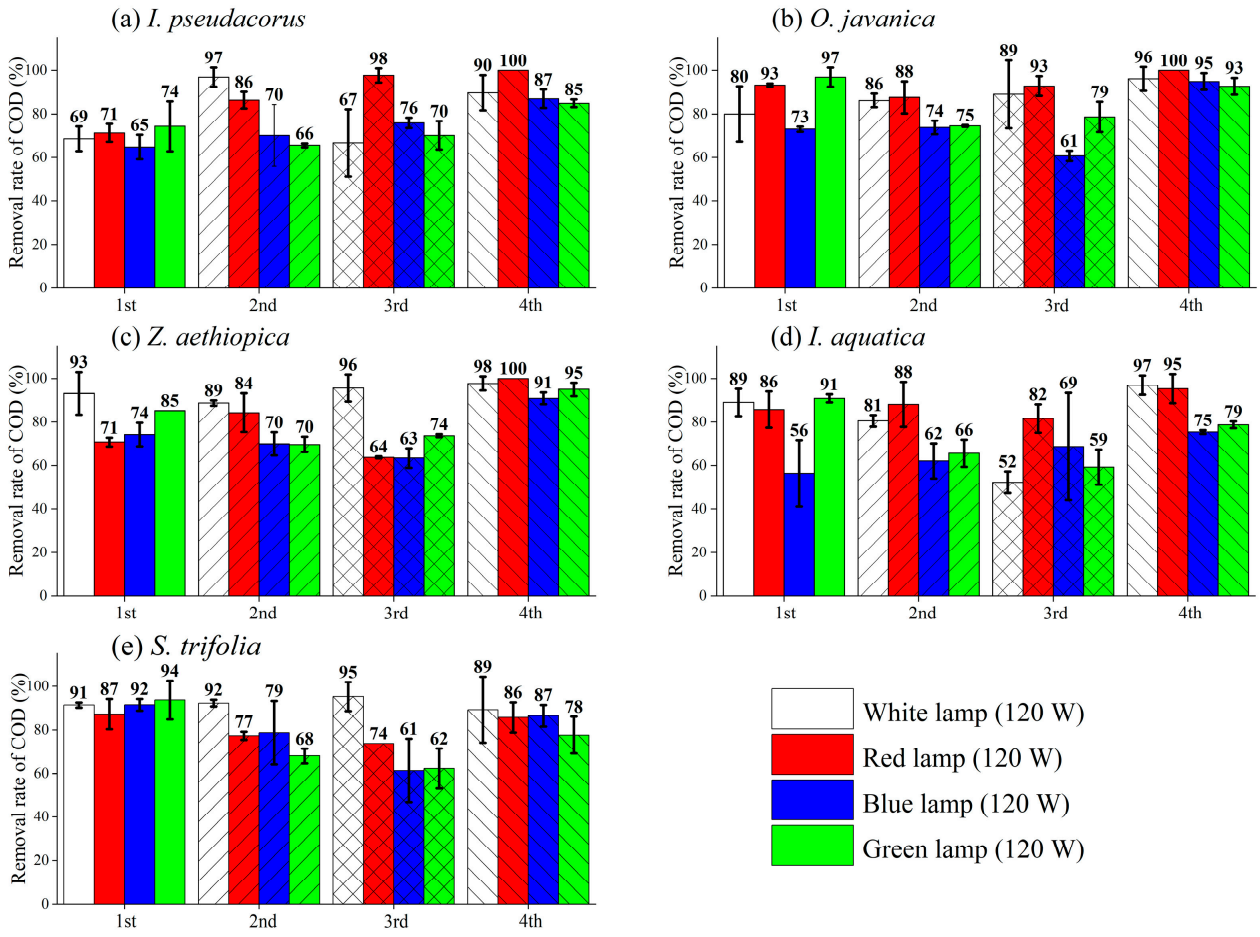

Figure 4. COD removal rates for five plants.

Phosphorus removal efficacy is a common endpoint for assessing the purifying capacity of an aquatic plant [33]. The figure depicts the distinct TP removal rates of selected plants and the different influences of monochromatic light radiation on removal rates (Figure 5). Overall, the ranking of TP removal rates for five plants was *S. trifolia* (white and blue lamps, 86.2%) > *O. javanica* (white, red and blue lamps, 76.5%) > *I. pseudacorus* (33.0%) > *I. aquatica* (32.3%) > *Z. aethiopica* (21.4%). For all five plants, the highest TP removal rates were determined under the conditions of white and blue lamp radiation; rates were moderate for the red lamp and lowest for the green lamp, respectively. These results show that green light radiation was not an essential factor in the P absorption of the tested plants. On the contrary, P absorption was facilitated by blue light radiation. For the effect of red light, the highest P removal rate was determined from *O. javanica*, a moderate rate was determined from *I. pseudacorus*, *I. aquatica* and *S. trifolia* and the lowest rate was determined from *Z. aethiopica*. The above results indicate that the wavelength of light played an important role in the P removal efficacies of plants. It was reported that the phytochrome B1, a red light photoreceptor, regulated the photo-response and nutritional control of plants; the increase in red light radiation positively regulated the absorption of P [34]. Aside from that, the root growth was increased by red light radiation, which facilitated the P absorption of *Poncirus trifoliata* [35].

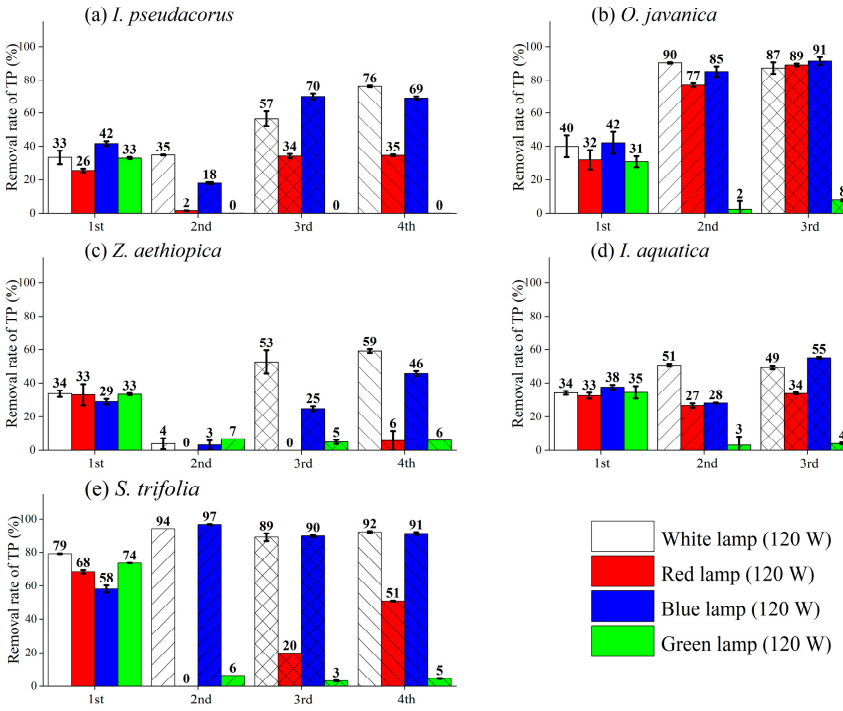

Figure 5. TP removal rates for five plants.

Using plants to remove nitrogen in effluent water is a biological method [36]. The rank of overall TN removal rates for the five plants was *S. trifolia* (37.3%) > *Z. aethiopica* (27.8%) > *I. pseudacorus* (24.2%) > *O. javanica* (15.0%) > *I. aquatica* (5.1%) (Figure 6). As compared to TP removal (from 21.4% to 86.2%), the overall TN removal rates (from 5.1% to 37.3%) were relatively lower. At the same time, we examined the influence of monochromatic light radiation on TN removal. The variation in TN removal rates under monochromatic light radiation as compared to the corresponding white lamp condition was around 20%, which was lower than that of TP removal, especially for *O. javanica* and *S. trifolia* under green light radiation (a more than 80% plummet was observed). This phenomenon suggested that TN removal was more complicated. For *I. pseudacorus*, a slightly higher removal rate was determined under blue light radiation. For *I. aquatica* and *Z. aethiopica*, the lowest removal rate was determined under green light radiation. During the removal of TN, the TN was not simply absorbed by plants; many redox reactions of nitrogen were produced concurrently, including nitrification and denitrification processes by microorganisms. Generally, the TN removal process by microorganisms was dominant as compared to digestion; the aquatic plants preferred NH_4^+-N to NO_3^--N, and the digestion processes were regulated by the concentration of nitrogen element and plant species.

Thus, the removal rates of TN did not significantly correlate with the radiation of monochromatic light. Thus, NH_4^+-N, NO_3^--N and NO_2^--N were determined to require further study on the influences of monochromatic light radiation on N-removal.

The removal rate of NH_4^+-N was influenced by the plant species and light radiation (Figure 7). The rank of overall NH_4^+-N removal rates for the plants was *S. trifolia* (white and blue lamps, 80.9%) > *I. pseudacorus* (blue lamp, 79.0%) > *O. javanica* (white and blue lamps, 70.9%) > *Z. aethiopica* (61.2%) > *I. aquatica* (33.2%). Overall, besides *I. pseudacorus* (more NH_4^+-N was removed under blue lamp radiation than that of the white lamp), the white light radiation provided a more convenient condition for NH_4^+-N removal than the three primary monochromatic light radiations did. Besides *Z. aethiopica* (the highest NH_4^+-N removal rate was determined under the red lamp condition as compared with other monochromatic light radiations), blue light radiation was more favorable to removing NH_4^+-N for the rest of the plants.

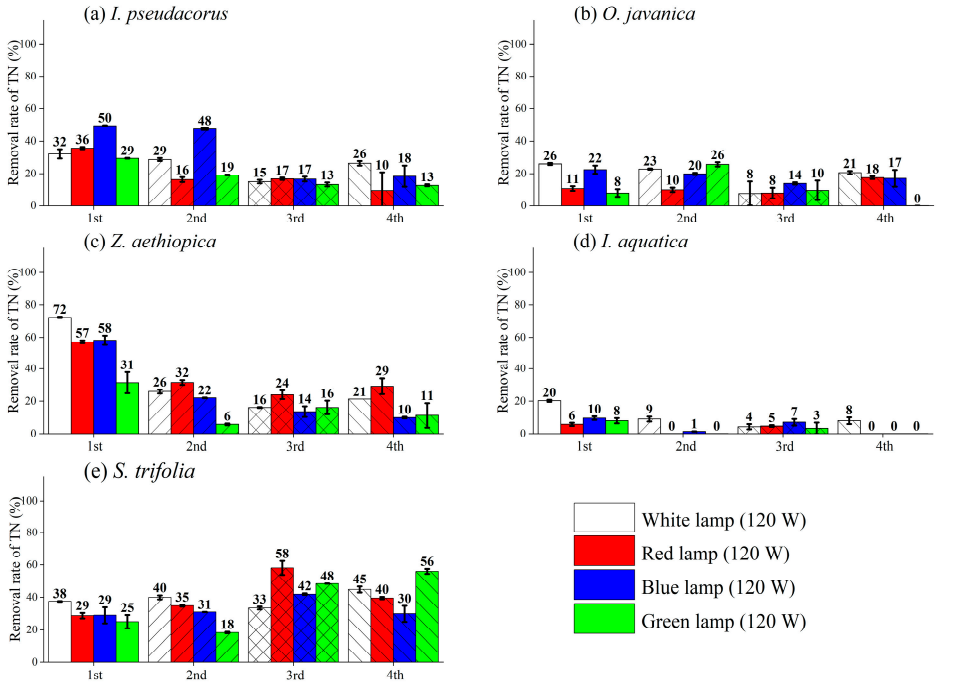

Figure 6. TN removal rates for five plants.

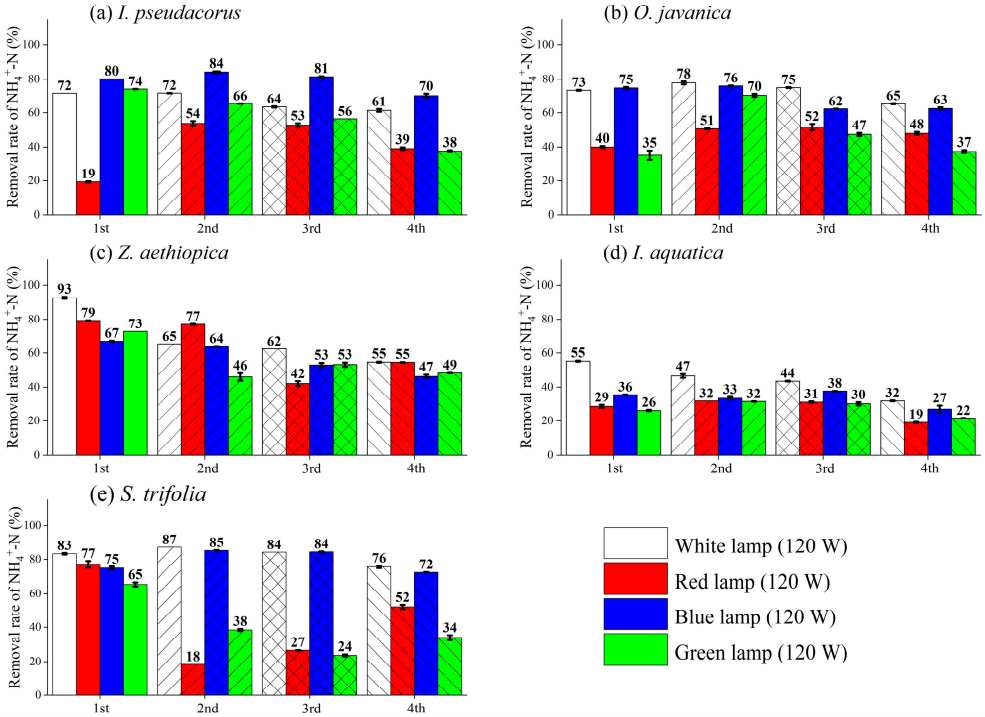

Figure 7. NH_4^+-N removal rates for five plants.

The rank of overall NO_3^--N removal rates for the five plants was *S. trifolia* (40.6%) > *Z. aethiopica* (31.6%) > *I. pseudacorus* (27.9%) > *I. aquatica* (14.5%) > *O. javanica* (13.1%); two tuberous plants (i.e., *S. trifolia* and *Z. aethiopica*) exhibited higher efficiencies in removing NO_3^--N than floating plants (i.e., *I. aquatica* and *O. javanica*) (Figure 8). Little influence was found for *I. aquatica* and *O. javanica* under different light radiation. On the contrary, *S. trifolia* and *Z. aethiopica* exhibited more NO_3^--N removal efficiencies under red lamp radiation as compared with other lamps. For *I. pseudacorus*, the blue lamp exhibited a relatively higher NO_3^--N removal rate than that of other lamps.

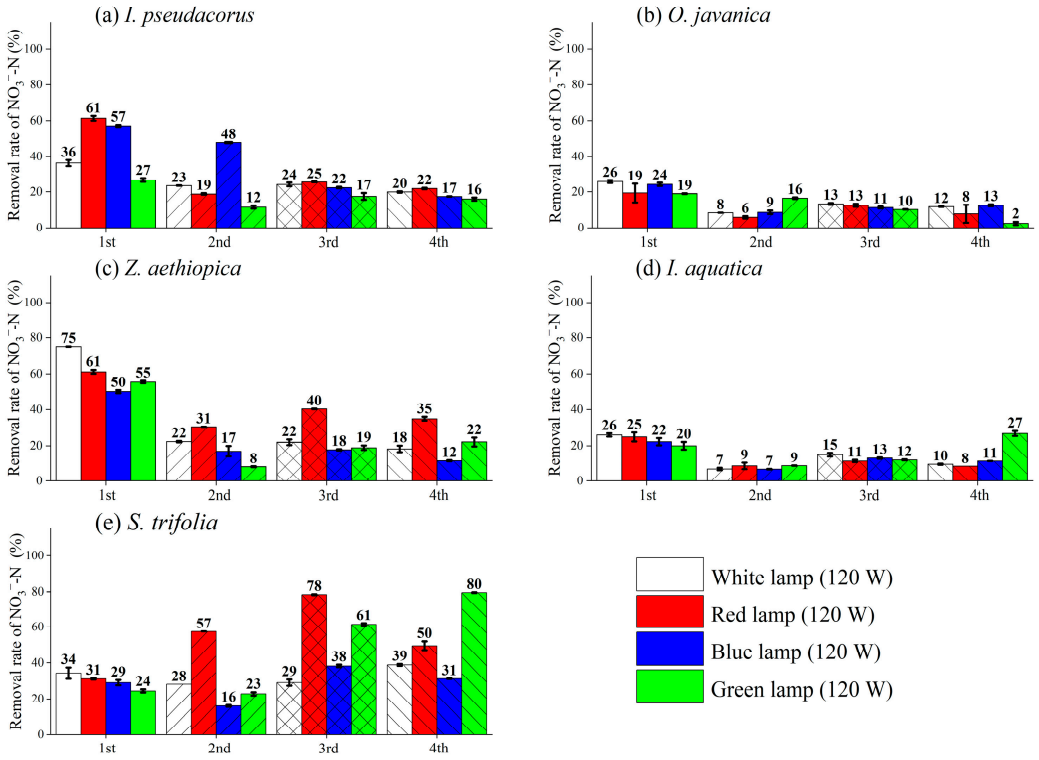

Figure 8. NO_3^--N removal rates for five plants.

The NO_2^--N concentrations of culture medium for five plants are shown in Figure 9. The NO_2^--N was not detected in the first cycle, and fluctuant values were determined in the other three cycles. No obvious pattern was found for the five plants under different light radiation in the experiment periods, which suggested that the nitrification and denitrification processes were irrelevant to monochromatic light radiation. There are certain differences in the concentration of NO_2^--N among different aquatic plants, which indicated that the nitrogen transformation process was greatly influenced by aquatic plant species. Overall, the *I. pseudacorus* had the greatest impact on the production of nitrate nitrogen, which indicated that the nitrogen conversion process was incomplete. The *I. aquatica* plant experimental group had a low concentration of nitrate nitrogen, which indicated that the plant promoted nitrogen conversion.

The content of chlorophyll for a plant was dependent on the environment. All tested plants showed different degrees of decline in the content of chlorophyll (from 46.5 to 36.3, 22.9 to 18.8, 27.1 to 16.5, 22.6 to 17.4 and 29.5 to 18.0 for *I. pseudacorus*, *O. javanica*, *Z. aethiopica*, *I. aquatica* and *S. trifolia*, respectively) (Figure 10). Out of the five plants, the *O. javanica* showed the least decline in chlorophyll content, which indicated that the *O. javanica* was easily acclimated to the condition of low nutrient concentration (COD = 50 mg/L, TN = 15 mg/L and TP = 0.5 mg/L). The *Z. aethiopica* and *S. trifolia* showed relatively higher chlorophyll content under red and green lamp radiation and lower values under blue light. For *I. aquatica*, the lowest chlorophyll content was determined under the green lamp. Similar results were found in the N content of leaves for the five plants (Figure 11). During the experiment, the N content and chlorophyll content of plant leaves were simultaneously determined at the end of each experimental period by using a TYS-4N Chlorophyll Analyzer (Beijing ZhongKeWeiHe Technology Development Co., Ltd., Beijing, China). The above results indicate that the accumulation of organic matters in plants was related to the light radiation.

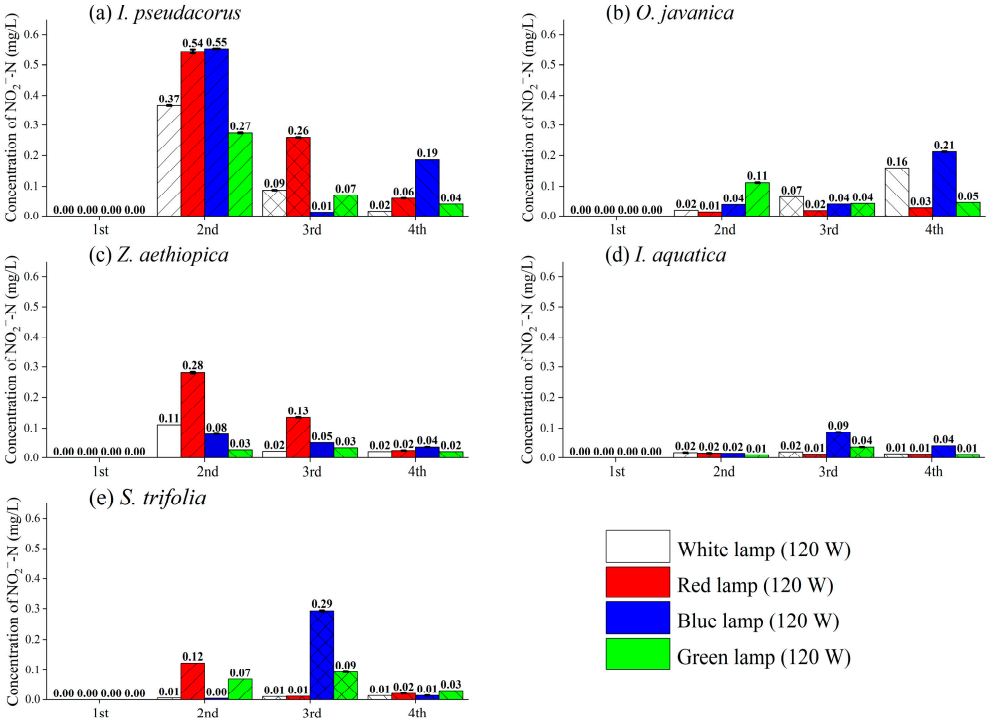

Figure 9. NO_2^--N concentrations of experimental culture medium for five plants.

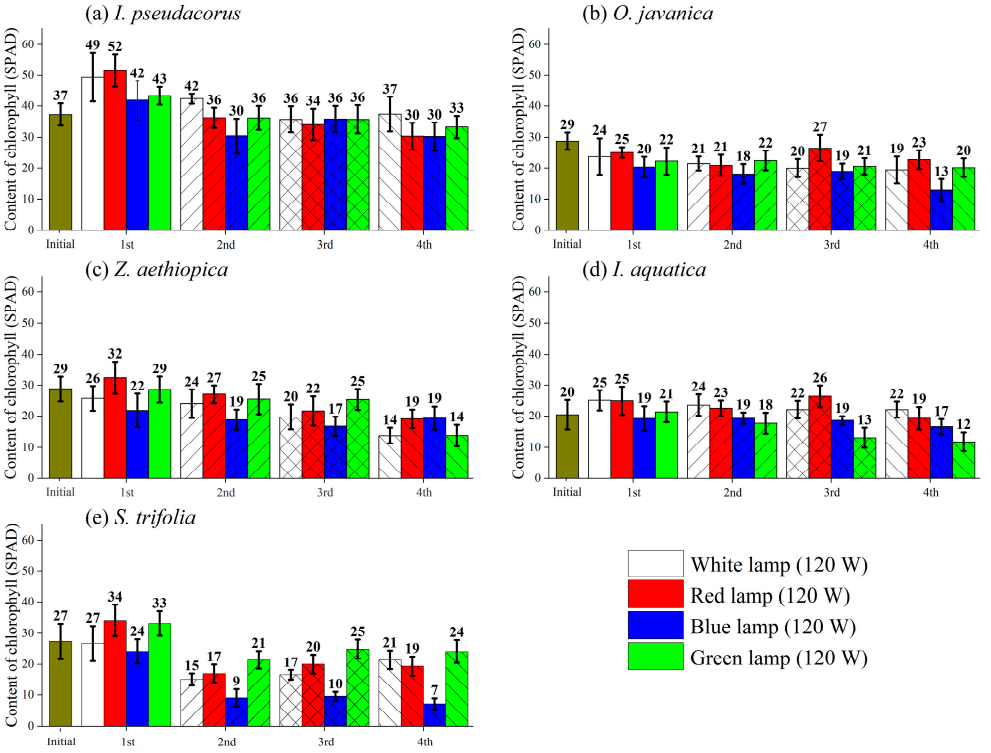

Figure 10. Chlorophyll content for five plants.

To observe the growth situation of five plants in the low-nutrient condition (COD = 50 mg/L, TN = 15 mg/L and TP = 0.5 mg/L), the weights of five plants were measured during the experiment periods (Figure 12). The results show that *S. trifolia* had the largest increase in the first cycle and a relatively higher increase in the remaining experimental periods. A relatively higher biomass increase was measured for *S. trifolia* under white lamp radiation as compared to other lamp radiation. The *O. javanica* showed a

relatively stable increase in the first three cycles and little increase in the last cycle, which suggested that this plant was able to grow healthily in nutrient stress conditions. For *Z. aethiopica*, a relatively higher biomass increase was measured under blue and green lamp radiation, which suggested that the biomass accumulation of *Z. aethiopica* was promoted by shortwave radiation.

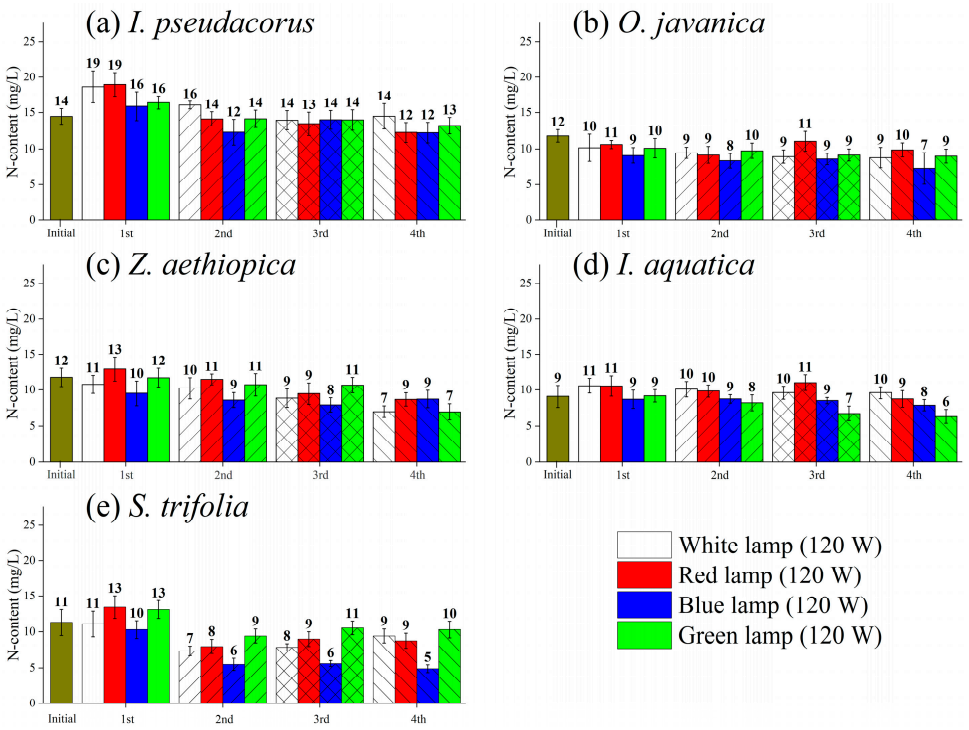

Figure 11. Plots of leaf N content for five plants.

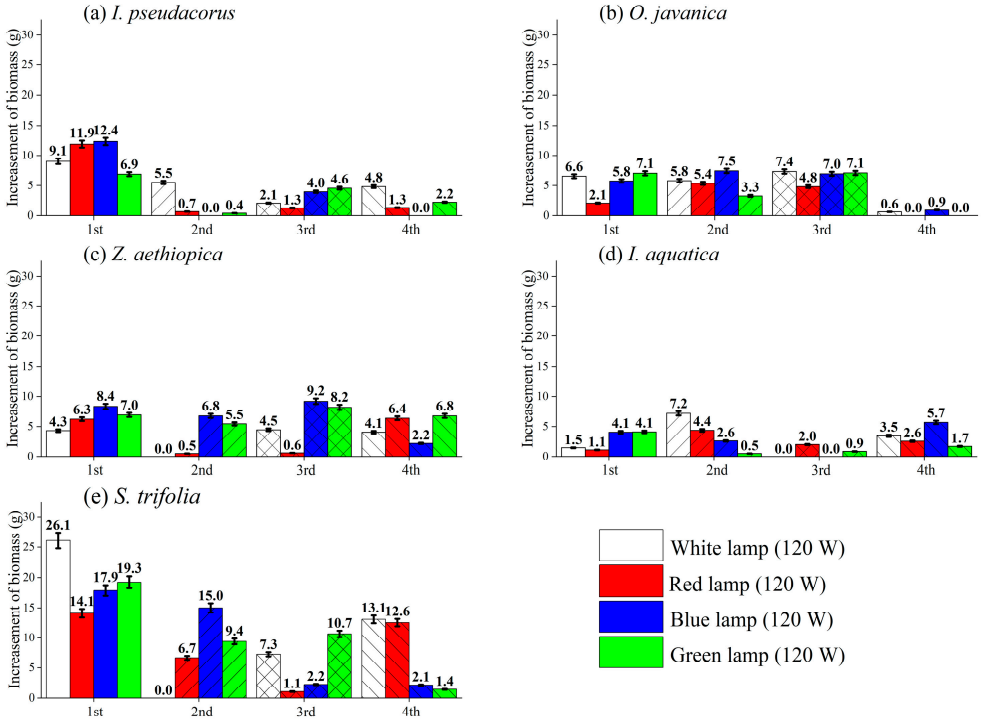

Figure 12. Biomass increasement for five plants.

4. Discussion

4.1. Growth of Aquatic Plants under Different Light

For the deep purification of municipal plant treated water by aquatic plants, one key limitation was the limited resource of carbon and nitrogen. The low concentration of nutrients influenced the growth status and limited the absorption and utilization of nitrogen and phosphorus [37–39]. Declining chlorophyll contents were determined for all tested plants; this phenomenon was caused by the absence of microelements and low content of TN and TP, which finally influenced the photosynthesis of plants [40]. In addition, the chlorophyll content of plants was influenced by the lighting spectra; the mean chlorophyll content of plants under blue light radiation was significantly lower than that under red light radiation, indicating that monochromatic red light was the most efficient light to accumulate chlorophyll for the five plants under low-nutrient conditions. Similar results were reported for *Boehmeria nivea* L. by activating photosynthesis and reducing reactive oxygen species accumulation [41]. It is noteworthy that the results do not mean red light promoted chlorophyll content as compared to other radiation; the low-nutrient condition (COD = 50 mg/L, TN = 15 mg/L and TP = 0.5 mg/L) played a key factor in the growth of tested plants. Under full-nutrient culture medium, the highest and lowest chlorophyll contents of *Chlorella ellipsoidea* were found in the blue and red light conditions, respectively [42]. Aside from that, under the well-cultured condition, blue light was the most efficient radiation for accumulating biomass for *Crocus sativus* L. [43] and *Brassica eruca* [44] as compared to other light sources. In this case, the biomass increase in *Z. aethiopica* was slightly higher than that for white light, and no significant difference was found for the rest, which indicated that the low nutrient level limited the growth of plants. Furthermore, the growth habit and environment requirement were key factors in growth status and N/P removal rates of plants. It was reported that the TN removal rate of *I. aquatica* was more than 30% in wastewater [45], but the TN removal rate was 10% in this case, which indicated that the growth habit of plants for water purification needed to be considered for the selection of plant species. At the same time, the plants released root exudates to their growth medium, including some ions and organic compounds [46], which exhibited reciprocal effects to the rhizosphere microorganisms for denitrification processes. TN removal should have been improved if the monochromatic light radiation increased photosynthesis and more organic matters were released into the water. In this case, the biomass increase was limited by the low-nutrient condition, and the root exudates diminished accordingly, which made contributions to the relatively low TN removal rates in the low-nutrient level.

4.2. Removal Efficiencies of N/P under Different Light

Although different aquatic plants exhibited various P removal rates, the blue light showed the highest P removal efficiencies and the green light showed the lowest efficiencies (Figure 5). These results indicate that light regulated the P nutrient absorption and blue light played a key role in absorbing the P in aquatic culture medium for the tested aquatic plants. Similar results were found in *Allium tuberosum* and *Allium sativum* L. [47]; the P content of these two plants under blue light radiation was higher than that for other lights. *Cucumis sativus* L. absorbed more P under red light radiation, which indicated that the different light effects were driven by plant species.

As compared to the removal of TP, the TN removal rates of the five plants were much lower. This phenomenon was induced by the low initial COD level, which posed a relatively low value for the COD-N ratio. It had been widely reported by many studies that low COD-N ratio influenced the N removal of plants by limiting the efficacies of functional bacteria, which participated in the nitrification and denitrification processes and finally inhibited the removal of N element [17,48,49]. The *S. trifolia* exhibited the highest efficiencies for N removal out of the five aquatic plants. Like the absorption of P, the absorption of N by *S. trifolia* was also influenced by the light quality. The overall TN removal rate under red light radiation (40.3%) was slightly higher than that of the

white lamp condition (38.9%), and the NO_3^--N removal rate under red light radiation (54.1%) was significantly higher than that for the white lamp (32.6%). Similar results were reported for microalgae and *A. tuberosum* [47]; the TN removal rate was significantly increased under red light radiation by activating the functional gene as compared to white lamp radiation [50]. On the contrary, the NH_4^+-N removal rate under blue lamp radiation showed the highest value (79.2%), above the three monochromatic light radiations and nearly equal to the white light condition (82.6%), which indicated that the NH_4^+-N uptake of *S. trifolia* preferred blue light radiation. The rest of the tested plants exhibited much lower N removal rates under the specific experimental condition, indicating that *S. trifolia* was a better choice for deep purification of N in low-pollution water.

It was reported that the red/blue light ratio of LED lamps influenced the growth and flowering quality of amaryllis as compared with the white LED light condition. The results show that a higher blue light ratio promoted the expression of the HpCOL gene and early flowering, whereas a higher red light ratio promoted vegetative growth but delayed flowering [51]. Aside from that, the variation in red/blue light ratio influenced the photomorphogenesis and steady-state photosynthesis of tomato (*Solanum lycopersicum*) [52]. From this, a deduction can be made that although sole monochromatic light radiation slightly promoted the N/P removal rates, the optimal condition for the red/blue light ratio is still needed for N/P removal in specific aquatic plants.

Based on the N/P removal results, a combination of aquatic plants and supplementary light conditions was selected for the deep purification of treated water. Namely, *O. javanica* and *S. trifolia* would be planted, and red and blue lamps would be used as supplementary light sources. On one hand, *O. javanica* was able to efficiently remove P in the treated water, and *S. trifolia* could remove N with high efficiency. On the other hand, the supplementary red and blue light efficiently increased the removal of N and P. The enhanced light intensity and prolonged light period effectively promoted the absorption of N and P for several plants. *C. sativus* absorbed more N and P if the light period was prolonged [47], *Gracilaria asiatica* exhibited higher efficiency in N and P absorption if the light was intensified [53] and the fresh weight of *Arabidopsis thaliana* showed significant enhancement when adding blue light radiation [54].

4.3. Application Prospect

For the deep purification of municipal plant treated water, the aquatic plant treatment system was usually employed. The aquatic plant species played a key role in the treatment system, which dominated the removal efficiency, retention time and running cost. In this case, the LED lamps were the only light source for the plants. Each chamber was 1.2 m^2 and 18 of the plastic containers used in this experiment could be set; the 8 h light period cost 0.96 kWh/d, and the energy cost could be significantly reduced if the LED lamps were used as supplementary light. At the same time, the LED lamps could be used as supplementary light in the night (22:00 to 6:00) and natural sunlight radiation could be used in the daytime (8:00 to 18:00), further improving the removal rates of TN and TP [55].

Outside of TN, the treated water quality matched the class III standard for natural surface water. TN removal was limited by the lack of COD, which offered energy and carbon sources for the microbial denitrification process. As a way out, biomass substrates such as biochar could be engaged by floating bed substrate [56]. On one hand, the biochar had a strong adsorption capacity for the dissolved substance, which facilitated the plant absorption of N-containing compounds. On the other hand, the biochar substrate fed active microbial communities and released supplemental carbon sources, which facilitated the removal of the N element.

As compared to the presented work, a batch of experiments contained 360 L of experimental sewage (COD = 66.0 mg/L, TN = 17.25 mg/L and TP = 1.89 mg/L) with 50, 50 and 100 strains of hyacinth, lettuce and *Myriophyllum spicatum*, respectively [45]. Under normal sunlit radiation in summer, the 4 d removal efficiencies of COD, TN and TP were around 60%, 20% and 25%, respectively, and those for 20 d were around 65%, 80% and 84%.

With similar initial plant biomass per acreage, much longer retention times were needed for hyacinth, lettuce and *Myriophyllum spicatum* than for *O. javanica* and *S. trifolia* in this case. At the same time, *O. javanica* and *S. trifolia* are two kinds of vegetables, the cultivation of the two plants can increase the profits, which furtherly promotes resource utilization for treated municipal wastewater.

5. Conclusions

The removal efficiencies of five aquatic plants (*I. pseudacorus*, *O. javanica*, *Z. aethiopica*, *I. aquatica* and *S. trifolia*) in low-pollution water and the impact of monochromatic light were determined. The main conclusions are as follows:

(1) During the experiment cycles, the *O. javanica* and *S. trifolia* exhibited relatively better growth status and higher TP removal rates (90%), and the blue light radiation played a key role in the TP uptake of the tested plants. Outside of TN, the treated water quality matched the class III standard for natural surface water. The biochar substrates could be engaged as floating bed substrate to increase N removal rates.

(2) *S. trifolia* exhibited the highest TN removal rate out of the five plants; red light promoted the removal of TN and NO_3^--N, whereas blue light was vital to NH_4^+-N removal.

(3) Based on these results, a combination of *O. javanica* and *S. trifolia* coupled with blue and red lamps as supplementary light was suggested for the deep purification of treated water or other low-pollution water conditions, which efficiently removed the N and P with relatively low cost. The optimal conditions for the intensity and ratio of monochromatic lamps for deep purification could be a direction for further research in the future.

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