Floating Islands Supported by LED Lighting: an Ecological Solution of Nutrients Removal from Municipal Wastewater?

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Abstract The aim of the study was to evaluate removal efficiency of nitrogen and phosphorus compounds by floating islands with macrophytes and influence of LED lights imitating the photosynthetically active radiation (PAR) on that effectiveness. Improving removal efficiency is crucial, thanks to ever-tightening legal requirements. Main reason for that is growing problem of eutrophication phenomenon. Nowadays, this problem is visible not only in lakes and ponds but also in water courses and coastal water. Study was conducted during time of 15 weeks. In that time, listed parameters were tested: pH, conductivity, total nitrogen, organic nitrogen, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, total phosphorus, and phosphates. Each tank was filled with same amount of biologically treated wastewater; ambient temperature and dissolved oxygen concentrations were kept in same range for the time of experiment. Average concentrations of main pollutants in tanks with LED lighting have reached: conductivity, 936 μS/cm; TN, 8.55 mg/dm³; P-PO₄, 0.74 mg/dm³; TP, 2.57 mg/dm³. In case of no LED lighting, concentrations of main pollutants have reached: conductivity, 949 μS/cm; TN, 12.85 mg/dm³; P-PO₄, 1.28 mg/dm³; TP, 2.54 mg/dm³. Based on observations and analyses, it can be concluded that the use of LED lighting imitating PAR radiation has positive effect on removal efficiency of total nitrogen and phosphates. Data suggests optimal time for treatment with floating islands as 13 weeks, extending that time to 15 weeks leads to degradation of treated wastewater quality instead improving it.

Highlights

• Floating islands supported with LED lighting are an alternative solution for nutrients removal.
• LED light intensifies nitrogen and phosphorus removal from municipal wastewater.
• The use of macrophytes in third stage of wastewater purification may result in increased nutrient removal efficiency.

Keywords Floating islands · Nutrients removal · Municipal wastewater · Nature-based solutions

1 Introduction

Following the ever-tightening legal requirements for removing nitrogen and phosphorus from wastewater, scientists are making continuous attempts to intensify sewage purification (Colares et al., 2020). The main reason forcing more efficient removal of nutrients is
the spreading eutrophication phenomenon. Nowadays, this problem is visible not only in lakes and ponds but also in water courses and coastal water (Andersen et al., 2019; Wurtsbaugh et al., 2019). Discharge of untreated or inefficiently treated wastewater, along with runoff from agricultural areas, is one of the main sources of nutrients inflow to natural water ecosystems. This problem is particularly evident in the age of industrialization increase and population explosion (Singh et al., 2017). Eutrophication can cause deterioration of water quality and affects the amount of water sources suitable for consumption purposes (Diatta et al., 2020). The harmful effects of eutrophication are also manifested by decrease of dissolved oxygen concentration and transparency of water, changes in flora and fauna population as well as by cyanobacteria and algae growth (algae blooms, cyanobacterial toxins) (Lu et al., 2019).

Eutrophication control is mainly based on nitrogen and phosphorus removal. It can be carried out using chemical reagents like lime Ca(OH)₂, alum Al₂(SO₄)₃·14H₂O, or ferric chloride Fe(Cl)₃ to precipitate phosphorus-rich chemicals (Boyd, 2020). Water aeration and bottom sediment removal are shown to be useful to reduce the risk of internal phosphorus fertilization in reservoirs. Also, a number of biological and even bionic methods have found use in eutrophication control (Qin et al., 2006).

One of the solutions for nitrogen and phosphorus reduction are floating islands (FI) tested almost all over the world. This solution might be used in natural reservoirs (to remove excess nutrients inflow) or in wastewater treatment plants (WWTP) as a technology for the third stage of wastewater purification focused on intensive nutrients removal. The main role in sewage purification with the use of FI pay macrophytes planted on specially prepared matrix enabling immersion of plant roots directly in the wastewater (Garcia Chance et al., 2019). Nutrients removal in such systems is mainly the result of macrophytes and microorganisms activity in aerated conditions (Masters, 2018). Additionally, the immersed roots of plants creates a filter for flowing wastewater enabling trapping of suspended particles (Shahid et al., 2018).

In wastewater treatment plants, the floating islands technology might be used in stabilization ponds or in hydroponic lagoons built in the shape of artificial rivers. The main factor which allows the use of technologies based on plants activity is availability of solar radiation and appropriate thermal conditions for macrophytes growth. Meeting these conditions can be difficult, especially in temperate climate conditions (Bawiec et al., 2018). To maintain the optimal conditions for sewage treatment with the use of FI and intensify the nutrients uptake by the macrophytes the use of additional lighting in the nighttime might be useful. The use of light-emitting diodes (LED) with the length of the emitted light wave in the range corresponding to photosynthetically active radiation (PAR) can improve the plants growth and effectiveness of nutrient uptake (Ma et al., 2014). Additionally, this kind of lighting has many advantages over the traditional sodium and fluorescent lamps—small volume and mass, long operating lifetime, low heat emission, adjustable light intensity, and length of the light wave (Lin et al., 2013).

The aim of the study was to assess the possibility of LED light use to support the nutrient uptake by macrophytes planted on the floating island used as an alternative way of municipal wastewater purification.

2 Materials and Methods

2.1 Experimental Setup

The study was conducted in laboratory conditions with the use of experimental setup consisted of two 60-L tanks with opaque walls. Each of the tank was filled up with 30 L of biologically treated wastewater taken from municipal wastewater treatment plant. Sewage in both of the tanks was aerated. On the sewage surface in both tanks, the floating islands consisted of plastic net with planted floating macrophytes Pistia stratiotes were placed. One of the tanks was equipped with artificial lighting system—two rails with LED in the color of blue (650 nm) and red (450 nm) in a 1:2 ratio. The emitted lengths of light corresponded to the length of photosynthetically active light (PAR). The experiment lasted 1.5 years and was divided into 6 measurement series. The picture of experimental setup during the day and at nighttime is presented on Fig. 1a, b.

2.2 Samples and Measurements

During the experiment, the environmental conditions like temperature of sewage and ambient air as well as
the dissolved oxygen concentration were measured regularly. The temperature of ambient air was kept in the range of 15–20 °C what allowed to keep very similar temperature of sewage in the tanks. The dissolved oxygen concentration was kept on the level of 9.5–10.8 mgO₂/l and measured with the use of portable oxygen meter (oxygen probe, HI9146-04).

Samples of wastewater from the tanks of experimental setup were taken generally every 2 weeks. Basic parameters like pH and conductivity as well as nutrients concentrations were measured with the use of methods and standards presented in Table 1.

### 3 Results and Discussion

The changes in basic parameters like pH and conductivity were similar in the tank with additional lighting and without it compared to the values measured in wastewater introduced into the tanks. The pH in biologically treated wastewater was close to 7.0 when in both of the tanks it was higher, reaching 9.0. These changes are characteristic for aerated wastewater where CO₂ is removed thanks to air addition. The changes in conductivity were similar—at the beginning of the experiment, conductivity was much lower than in the tanks after purification time where it varied from 730 to 1375 μS/cm as a result of microbiological activity. For all parameters, the statistical t-Student test and the Kruskal–Wallis test were performed, which showed a statistically significant difference between the concentrations of N-NO₃ and P-PO₄. The average values of selected measured parameters for the whole experiment are presented in Table 2.

To assess the role of LED lighting in wastewater purification improvement while using floating islands, the changes of nutrients concentrations during the longest measuring series (15 weeks) were analyzed. Obtained results were compared to the mean values of nutrients concentrations observed during the whole experiment (1.5 years). Results of analyses obtained

### Table 1 Methods and standards of wastewater quality measurements

| No | Pollutant indicator       | Methodology of research                  | Standard                        |
|----|---------------------------|------------------------------------------|---------------------------------|
| 1  | pH                        | Potentiometric method                    | PN-EN ISO 10523:2012            |
| 2  | Conductivity              | Conductometric method                    | PN-EN 27,888:1999               |
| 3  | Nitrates                  | Spectrophotometric method                | PN-82C-04576/08                 |
| 4  | Nitrites                  | Spectrophotometric method                | PN-EN 26,777:1999               |
| 5  | Ammonium nitrogen         | Spectrophotometric method                | PN-ISO 7150:2002                |
| 6  | Total nitrogen            | Specific method                          | PN-EN 25,663:2001               |
| 7  | Organic nitrogen          | Computational method                     | PN-73/C-04576–14                |
| 8  | Total phosphorus          | Spectrophotometric method with HNO₃ mineralization | PN-EN 1189–2000 |
| 9  | Phosphates                | Spectrophotometric method                | ISO 6878/1:2006                 |
for sewage with and without LED lighting are presented on Figs. 2 and 3.

It is visible that the average total nitrogen (TN) concentration during the whole experiment was lower in the tank with additional light source and it was 8.55 mg/dm³. In the tank with LED, the concentration of TN dropped after 4 weeks of experiment comparing to the value examined in sewage from WWTP poured into the tank (START). After next 2 weeks, it reached the highest peak and started to decrease. In the last 5 weeks of experiment, the TN concentration was lower than the average value calculated for all measuring series. Concentration of total nitrogen in the tank without additional lighting was higher than in the other tank during the whole series duration. The curve course on the graph has similar shape like in the tank with LED—the highest peak is also observed in 6th week of experiment but it is not as high as in the other tank. The concentrations during the series were lower than the average value for more than 13 weeks while in the last day of the experiment it exceeded 12.82 mg/dm³.

Total phosphorus (TP) concentrations showed different dependence—the average concentration was slightly higher in the tank with LED. In both cases, the concentrations of TP during the analyzed measurement series were lower than the average identified for all series in the experiment. In both tanks, the highest peak of concentration occurred in 4th week of experiment and then started to decrease until the

| Table 2 Averag values of selected measured parameters for the whole experiment (6 measurement series) |
|---------------------------------|--------|------|------|------|------|------|------|------|------|
|                                | pH    | Cond | TN   | N_\text{org} | N-\text{NH}_4 | N-\text{NO}_2 | N-\text{NO}_3 | P-\text{PO}_4 | TP     |
| LED O₂ Unit Average            | 8.30  | 936  | 8.55 | 2.67          | 0.15           | 0.06           | 5.65           | 0.74           | 2.57   |
| Median                         | 8.30  | 919  | 8.79 | 2.20          | 0.03           | 0.01           | 6.14           | 0.07           | 1.24   |
| Min                             | 7.70  | 730  | 2.46 | 0.07          | 0.00           | 0.00           | 0.15           | 0.00           | 0.00   |
| Max                             | 9.00  | 1288 | 15.41| 9.20          | 2.37           | 0.70           | 9.14           | 3.73           | 9.53   |
| Standard deviation              | 0.31  | 119  | 2.91 | 1.65          | 0.49           | 0.15           | 2.37           | 1.34           | 2.89   |
| NO LED O₂ Average              | 8.30  | 982  | 12.82| 2.00          | 0.13           | 0.03           | 10.23          | 1.28           | 2.54   |
| Median                         | 8.40  | 949  | 12.85| 1.99          | 0.03           | 0.01           | 9.74           | 0.67           | 1.71   |
| Min                             | 5.90  | 740  | 1.28 | 0.16          | 0.00           | 0.00           | 1.06           | 0.00           | 0.00   |
| Max                             | 9.00  | 1375 | 19.64| 4.36          | 2.00           | 0.32           | 17.52          | 4.31           | 8.48   |
| Standard deviation              | 0.59  | 147  | 3.86 | 3.86          | 0.41           | 0.06           | 4.01           | 1.33           | 2.16   |

Fig. 2 Concentration of total nitrogen during the longest measurement series compared with the average value for all series in tank with LED lighting at night and without artificial light source.
13th week. During the last 2 weeks of the series duration, the concentration of TP increased and reached higher final value in the tank without artificial light source—2.09 mg/dm³. In both experimental tanks, the TP removal achieved the highest efficiency at week 13th. Extending the duration of the experiment to 15 weeks worsened the quality of the wastewater. Distribution of pollutant concentration values in the last measurement series with the duration of 15 weeks is presented on Figs. 4, 5, 6, 7, 8, and 9.

The concentration of total nitrogen during the 15-week measurement series was visibly higher in the tank without additional light source. At the same time, the concentrations of organic nitrogen were similar in both tanks. During the experiment, the extreme values occurred in the tank with LED lighting both in the case of total and organic nitrogen which is closely related. Because of similar organic nitrogen concentrations, the rise of total nitrogen value in the tank without lighting is not related to algae growth observed in the tank during the experiment as its removal efficiency is mostly based on nitrification and denitrification and not bioaccumulation. Although efficiency of those processes is related
to symbiosis between plants and biofilm, which could account for higher efficiency of total nitrogen removal (Bi et al., 2019).

The concentrations of nitrogen compounds like ammonium nitrogen and nitrite nitrogen show similar values for both of the tanks. A slightly larger range of values was observed for ammonium nitrogen in the tank without artificial light source. The differences are visible for the nitrate nitrogen concentrations. The range of values for the sewage from tank
without additional lighting is larger as well as the concentration values themselves. Lower concentrations of ammonium and nitrate nitrogen in the wastewater from the tank with LED lighting result from the increased uptake of these nitrogen forms by more intensively developing plants and algae than in the tank without light. It could be also caused by higher nitrification and denitrification rates (PAR light).

In the case of total phosphorus concentrations, the range of values and the median is larger in the
wastewater from the tank without LED lighting. The concentrations of phosphates are lower in the tank with the artificial light source, because P-PO₄ as the form of phosphorus available for plants uptake was more intensively absorbed by developing macrophytes and algae.

Organic phosphorus is degraded by bacteria to phosphates; degradation of phosphorus might be increased by better developed root system, which is more developed thanks to increased photosynthesis ratios and thus symbiosis between bacteria and macrophytes (Bi et al., 2019). This might account for better removal efficiency of total phosphorus then in tanks without led lights in place.

On the basis of wastewater quality at the beginning of the experiment (wastewater after biological treatment) and the quality of wastewater from experimental setup tanks with additional LED lighting and without artificial source of light, the efficiency of sewage treatment was determined. The efficiency removal of contaminants is presented in Fig. 10.

Based on the results of nitrogen and phosphorus compound removal efficiency and the concentrations of individual pollutants, it can be concluded that the use of floating panels with macrophytes positively affects the removal of total and organic nitrogen as well as the phosphates from the treated sewage. The removal of ammonium nitrogen and nitrites is the same in both systems what results from nitrogen transformations taking place in aerated tanks also because of nitrogen compound transformations the N-NO₃ concentrations increased in both tanks (the negative values of removal efficiency). However, the increase of nitrate nitrogen concentration in the tank with LED lighting was much smaller than in the tanks without light source where it exceeded 160%. It was due to macrophytes activity and the intensified N-NO₃ uptake in the tank with LED. Phosphates were completely removed from the system with lighting where in the tank without LED the increase of P-PO₄ concentration reached more than 55%. In the case of total phosphorus removal, in both cases, the increase of this compound was observed. However, in the tank with artificial lighting, thanks to P-PO₄ uptake by the plants, the increase was three times smaller than in the tank without light source.

4 Conclusions

Based on the results obtained after 1.5 years of the experiment, it can be concluded that the use of
floating islands with macrophytes enables the reduction of total nitrogen, organic nitrogen, phosphorus, and phosphates concentrations.

The removal efficiency of total and organic nitrogen can be increased by the use of artificial lighting with LED in the color of blue (650 nm) and red (450 nm) in a 1:2 ratio, imitating the photosynthetically active radiation (PAR).

The additional lighting does not affect the removal of ammonium and nitrite nitrogen. The removal efficiency of these forms of nitrogen results from changes in nitrogen occurring under the conditions of aeration. Because of the same reason, the increase of nitrate nitrogen was observed in both of the tanks.

In both of the systems, the increase of total phosphorus was observed but in the case of the tank with artificial lighting where the phosphates uptake by the macrophytes and algae is higher; the P_total concentration in the end of the experiment was smaller (with increase of phosphorus almost 3 times lower). In terms of phosphates 100% reduction with led lighting was possible; without led lighting, there was increase of concentrations of phosphates by 55%.

Total nitrogen and phosphorus showed reduction till 13 week of operation. Increase of those parameters occurred at 15 week of operation.

Based on the presented data, it can be concluded that the optimum time of wastewater purification in the hydroponic system with the floating macrophytes panels is 13 weeks, because, after that time, the concentrations of selected parameters increased comparing to the concentrations identified in the 13th week of the experimental setup duration.

Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of Interest The authors declare no competing interests.
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