Effect of Integrating LED Lighting With Fiber Membranes On The Restoration of Eutrophic Waterbody And Its Optimal Application

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Abstract

In this study, laboratory experiments were used to compare the effects of two LED light sources (blue and red) combined with fiber membranes on the increase of Dissolved Oxygen (DO) in eutrophic water bodies for improvement of water quality. The results showed that the application of these two LED light sources can increase the DO concentration and oxidation-reduction potential (ORP), and eliminate the NH_4^+-N in water bodies and the phosphorus release from the sediment, resulting in the improvement of sediment. Specifically, the blue LED light source is more benefitable to the increase of the DO concentration than the red LED light source. After 28 days, the DO concentration increases to 10 mg/L, and the redox potential is higher than 50 mV with the elimination of NH_4^+-N. This study illustrated that LED light sources can significantly increase the DO and effectively improve the water quality in eutrophic water bodies.

Introduction

The eutrophication of closed waters, such as lakes and reservoirs, has become a global water environmental problem. According to statistics, more than 75% of closed waters in the world have eutrophication problems (Nie et al., 2014). In 2017, among the 109 lakes (reservoirs) in China which were monitored nutritional status, 33 lakes (reservoirs) had reached eutrophication, accounting for 30% (Tong et al., 2017). Lake eutrophication can cause the functional degeneration of the lake ecosystem and the frequent occurrence of cyanobacteria blooms in water bodies. The algal toxins secreted by cyanobacteria threaten human health and cause substantial economic losses(Graham et al., 2018).

The control measures of eutrophication can be classified into physical, chemical, and biological methods. Physical methods such as dredging, covering, water dispatching are time-consuming and labor-intensive (Zhen et al., 2011; Yang et al.,2011). Although chemical methods such as flocculation and adsorption can quickly take effect, the treatment cost is high, and the secondary pollution cannot be ignored (Schindler et al., 2012). Bioremediation methods include biological agents and immobilized microorganism technologies(Hyytiainen et al., 2015), which can improve water quality environmentally friendly at a low cost, resulting in hotspots in the research field. However, while using exogenous microorganisms to promote the biodegradation of polluted water bodies is also be at a disadvantage in the competition with native microorganisms due to their inability to adapt to the local ecological environment, eliminating the effects of degradation, which may also threaten the ecosystem(Ojuederie et al., 2017).

In long-term coexistence with the environment, the indigenous microorganisms formed a stable aggregation structure adapted to the environment, effectively using and decomposing organic matter in the environment for a long time (Satyanarayana et al., 2012). The low dissolved oxygen (DO) concentration in the water body inhibited indigenous microbial activity, so the reproduction of indigenous microorganisms should be promoted. Local microbial growth-promoting technologies mainly include river exposure gas and bio-promoting agent technologies (Guo et al., 2014). However, these methods have limitations in the long-term application process, such as high cost and water deterioration by adding microbial growth promoters to the sediment (Yang et al., 2020). Therefore, economical and environment-friendly methods are necessary for eutrophication management.

Light-emitting diode (LED) was widely used for micro-algae culture and plant growth (J González-Camejo et al., 2017), but few studies applied the LED technologies for water improvement in eutrophic water. This study aims to relieve the eutrophication by low DO in the bottom, and fiber membrane combined with LED was applied to activate the indigenous photosynthetic microorganisms in the bottom mud. LED provided a light source for microbial proliferation and algae photosynthetic oxygen evolution, and fiber membranes enhanced microbial growth by the attachment. Finally, the purification of eutrophic water by this combined process was investigated.

Materials And Methods

2.1 Materials

The experimental water and bottom mud were collected in the artificial lake at Zhongshan Park, Wenzhou, Zhejiang, China. The sediment was sampled at the bottom of the river using a Peterson dredger to remove debris and gravel. A sealed black plastic bag was used to store the sediment and delivered to the laboratory for the experiments. The lighting LED strips (NVC-3528/5050, NVC Lighting Holding Limited, China) were used for red/blue LED lighting in this experiment. The polyester fiber was applied for the application of fiber membrane.

2.3 Experimental method

The laboratory experiments were operated in 3L beakers of 4 groups with replicates. The sediment of 5 cm was set in all laboratory experiments, and the water level was 25cm from the mud-water interface using the siphon method. The experimental groups were set as follows: Group E (control group) with sediment and water; Group D with a fiber membrane of 5 cm from the upper part of the mud-water interface; Group A and B with a fiber membrane 5 cm from the mud-water interface, and circles of blue LED and red LED light strips were installed on the outer wall of the beaker, respectively. The opening of all the experimental beakers was covered to simulate low DO concentration in eutrophic water. Experimental groups E and D were performed in the dark place. A and B experimental groups were performed with covered sediments. All the experimental beakers were placed in a constant temperature incubator with 25 ^{o}C. Samples were collected every 7 days, and water in the upper and lower layers of the fiber membrane was collected to analyze the water quality.

2.4 Analytical method

COD_{Cr}, NH_4-N^+, TN, TP, PO_4^{3-} are determined according to Chinese national standard methods (PRC State Environmental Protection Administration, 1998). Turbidity is measured by HACH2100Q desktop turbidity meter. DO, pH, oxidation-reduction potential (ORP), and electrical conductivity (EC) were measured using the HACH40d probe method.

Results And Discussion

3.1. Appearance changes of sediments

On the 14th day of the experiment, the sediment color of the E group (control group) and the D group (non-lighting group) were black. For the eutrophic waterbody, microorganisms decompose the organic matter in the water body and consume DO in the water, causing an anoxic or anaerobic state in the water body for a long time. Facultative bacteria and anaerobic bacteria decompose the organic matter to produce gas such as ammonia and hydrogen sulfide, metal ions combined with sulfide ions, produced black-causing substances. Insoluble suspended particles and colored humus in the water are deposited to form black and odorous sediment (Kong et al., 2021). Compared with the control group, the color of the sediment in the two groups of A (blue) and B (red), applying LED lights, changed from black to ocher significantly, and the improvement by group A (blue) was better than group B (red). These results indicated that LED lighting devices provided a light source for the photosynthetic oxygen release of benthic algae, increasing DO (Zhang et. al, 2015), and enhancing the activity of microorganisms to accelerate the degradation of organic matter in the sediment. Besides, the aerobic condition can oxidize Fe^{2+} and H_2S, black and odorous reducing substances, to eliminate the black and odor of the sediment, resulting in sediment remediation in the eutrophic waterbody.

3.2. Improvement of Water Quality

3.2.1. pH and Turbidity

As shown in Fig. 1, the water pH in the upper and lower layers of the fiber membrane in the control group E ranged from 7 to 7.5 during the experiment period. Compared with the control group, the pH values of the upper and lower water bodies of the experimental group D decreased to 6.9 and 6.8, respectively, on the 7th day. During the experiment, the water pH values in the upper and lower layers of the fiber membrane of experimental group A showed a trend from rising to decline between 7 and 7.5; the pH values of the upper and lower water bodies of experimental group B declined firstly and then increased between 7 and 7.5. The insignificant changes in pH can be attributed to the factors as follows: the CO_2 consumption by the growth of algae in the water body, leading to an increase in pH value (Tsai et. al, 2012). Furthermore, in the two groups irradiated by LED lights, the proliferation and activity of microorganisms proliferate are enhanced, resulting in the carbonic acid and organic acids secreted in the metabolic process to decrease pH value (Hurst et. al, 2012). Therefore, the balance of pH was expected in this experiment.

The turbidity results were shown in Fig. 2. The turbidity of all experimental groups decreased significantly during the experiment. The turbidity of the lower layer of the fiber membrane was higher than that of the upper layer of the fiber membrane, which was attributed to the bottom layer of the experimental group illuminated by LED lights, resulting in the phytoplankton proliferation in the water body. In addition, the mechanical blocking effect by the fiber membrane can contribute to the turbidity difference between the upper and bottom layers.

3.2.1. DO and ORP

The change of DO is shown in Fig. 3. In the control group E and experimental group D, the DO concentration in the upper and lower layers of the fiber membrane ranged from 0.3 to 0.5 mg/L. In experimental group A, the DO concentration increased rapidly and peaked on the 7th days, and the DO concentration in the upper and lower layers of the fiber membrane increased from 0.38 mg/L to 11.85mg/L and 10.88mg/L, respectively. In experimental group B, DO concentration showed a trend from rising to decline, increasing DO concentration at 0.81 mg/L and 0.50 mg/L, respectively.

In the early stage of the experiment, LED light promoted the photosynthetic oxygen evolution of algae resulting in the DO concentration increased rapidly. However, the rapid proliferation of microorganisms and phytoplankton also consumed a large amount of oxygen, which caused the DO concentration to decrease in the later stage. Although the fiber membrane has no effect on increasing DO concentration, its combination of LED light can effectively increase the DO concentration. Furthermore, the LED blue light has a more significant effect on the increase of the DO concentration of the water body than the LED red light. When external source pollution is controlled, the release of internal source pollution becomes the main influencing factor of eutrophication, and DO is the main inducement factor that affects the release of the internal source(Ma et al., 2006). The in-situ microbial remediation of sediments towards the endogenous load has become a research hot spot. Among them, maintaining the aerobic environment of the water body is a necessary prerequisite for in-situ bioremediation.

DO level is an important condition to limit the growth of microorganisms (Jiang et al., 2019). Xiang (Xiang et al., 2013) proved that strengthened the indigenous microbial functional bacteria HC-1 through aeration can significantly improve the overlying water quality of black and smelly rivers and speed up sediments repair. Piasecki and Michael (Piasecki and Michael, 2004) had shown that increasing DO can restore and enhance the vitality of aerobic microorganisms in the water body, thereby improving the water quality. This study confirms that the DO concentration of water bodies can be significantly increased by LED lighting, and the DO concentration of the blue LED lamp group increases more significantly. The illumination of LED lights can provide a light source for the growth of benthic algae in eutrophic water bodies and increase the DO concentration in the water body through algal photosynthetic oxygen evolution. The results of Jiang's research (Jiang et al., 2019) pointed out that the overall growth of benthic algae communities is red light sensitive. In this study, it was also observed that the algae grew rapidly in the beaker of the red LED lamp group, but after the algae proliferation reached a certain level, the restriction of environmental conditions caused the algae to begin to die out in large numbers. Microorganisms consume a lot of DO to decompose dead algae,so the increase in DO concentration of the red LED lamp group is smaller than that of the blue LED lamp group and shows a downward trend in the later experimental stage. The ORP values of groups A and B with light exposure also increased significantly, which is closely related to the DO concentration of the water body. The experimental groups A and B both showed a trend of first increase and then decreased. This is because the number of microorganisms increased with DO in the later period of the experiment. The use of organic matter to multiply by microorganisms will lead to a local anaerobic environment, resulting in decreased redox potential (Song et al., 2013).

Figure 4 showed that the ORP values of the blank group E had been below − 50mV during the experiment, and the ORP values of the experimental group D decreased rapidly with stabilization at around − 200mV during the experiment, with the ORP value of the lower layer of the fiber membrane was consistently lower than that of the upper layer. ORP values of the experimental groups A and B increased significantly. They peaked at about 150mV on the 14th day of the experiment, indicating that the ORP value was significantly higher than that in the initial stage with the ORP value of LED blue group A above LED red group B. The ORP value reflects that the water bodies of the control group D and the experimental group E have been in a reducing state, which is fit for the results of DO concentration (Fig. 3) that these two groups were under the anaerobic condition. The increase of DO can increase the ORP value (Wang Q et al., 2011). the ORP value of the experimental group A and B water body changes from negative to positive by increasing DO. The state changes to the oxidation state, which benefits the removal of organic pollutants.

Many factors could affect the ORP of water bodies, such as pH, light, temperature, metabolic activities of microorganisms and metabolites, DO, etc. (Gui et al., 2007). From the apparent change characteristics of each experimental group, it can be seen that in the two groups illuminated by LED lights, the color of the bottom mud surface changed from black to a normal situation. The main reason is, with the growth of the content of DO, the activity of microorganisms increases, and the proliferation of benthic phytoplankton accelerates the degradation of organic matter in the bottom mud. The aerobic environment can also oxidize the reducing substances, such as Fe^{2+} and H_2S, which cause the black and odor of the bottom sludge. Thus, eliminating the black and odor of the bottom mud can gradually restore the normal color of the bottom mud.

3.2.3. NH_4-N, NO_3-N, and TN

The initial NH_4-N concentration is about 7mg/L, but the NH_4-N concentrations of the blank control group E are approximately 11 mg/L, and the NH_4-N concentrations of the experimental group D are 11.38 mg/L and 14.90 mg/L, which higher than the initial value of the experiment significantly. However, the NH_4-N concentration of the experimental groups A and B with LED light decreased significantly with the NH_4-N concentration in groups A and B decreased below 1mg/L on the 14th and 21st days, respectively, indicating that the LED blue (A group) can eliminate ammonia more efficiently than that of the LED red group B.

The results of NO_3^--N were shown in Fig. 5. The NO_3^--N concentration of the control group E increase and peaked on the 21st day and then decreased. At the end of the experiment, the upper and lower layers of the fiber membrane's concentrations were 3.29 mg/L and 2.96 mg/L. In experimental group D, the NO_3^--N concentration increased with final NO_3^--N concentrations in the upper and lower water bodies were 1.03

mg/L and 2.38 mg/L, respectively. Besides, the NO_3^--N concentration of experimental groups A and B containing LED lights increased and then declined during the experiment. By the end of the experiment, NO_3^--N concentrations of experimental groups A and B were about 1 mg/L, which is significantly higher than the 0.11 mg/L at the initial stage. The water bodies of the experimental group D and the control group E had been in the state of anaerobic for a long time, and the NO_3^--N in the bottom sludge is released to the overlying water body, causing the concentration of NO_3^--N in the overlying water body to increase, which is also consistent with the change of total nitrogen (Fig. 6). The NO_3^--N concentration of the groups A and B illuminated by LED lights showed an increasing trend with lower than that of the control group E and the group D. This is attributed to that the states of groups A and B illuminated by LED lights changed from anaerobic to aerobic, resulting in the suppression of the nitrogen release in the bottom sludge. Besides, nitrifying bacteria activity had enhanced, and the NH_4-N released into the water body is converted to NO_3^--N by nitrifying bacteria, contributing to its accumulation.

As shown in Fig. 5, the initial TN concentration of the experiment was 8.59 mg/L. At the end of the experiment, the TN concentration of the upper and bottom layers of the blank control group was 19.5 mg/L and 16.87 mg/L, respectively, and the TN concentrations in the upper and lower layers in the experimental group D were 15.3 mg/L and 19.8 mg/L, which were significantly higher than the initial concentration. The TN concentration of experimental groups A and B increased on the 7th day and showed a declining trend in the subsequent experimental stage. At the end of the experiment (the 28th day), TN concentrations of the upper and lower layers in group A were 1.55 mg/L and 1.92 mg/L, respectively. TN concentrations of the upper and lower layers in group B were 1.93 mg/L and 1.89 mg/L, respectively. Compared with the initial value, the TN concentration in the two groups containing LED lights decreased significantly, which were both below 2 mg/L. In the experiment, groups A and B containing LED lights have a good removal effect on ammonia nitrogen. Among them, the removal rate of blue LED lights is faster. With the increase of DO, the water body changes from anaerobic to aerobic; through nitrite bacteria and nitrate bacteria, oxidized ammonia nitrogen into nitrite nitrogen and nitrate nitrogen. With microbial activity enhancers and zooplankton growth, a large amount of DO is consumed in the water body, causing a local anaerobic environment in the water body, leading to simultaneous nitrification and denitrification beneficial to the nitrogen removal.

3.2.4. TP

As shown in Fig. 7, the TP concentration in the control group E gradually increased, and the upper and lower water bodies increased from the initial 0.11 mg/L to 1.21 mg/L and 1.38 mg/L, respectively after 7 days. After 28 days, the TP concentrations in the upper and lower layers were 1.20 mg/L and 1.14 mg/L, respectively. The concentration of TP in the upper and lower waters of the fiber membrane of experimental group D continued to rise during the test, and the TP concentration of the water under the fiber membrane increased significantly compared with the lower layer. At the end of the experiment, TP concentration in the upper and lower layers of the fiber membrane reached 0.89 mg/L and 2.42 mg/L. The TP concentration of the upper and lower water bodies of the experimental group A fiber membrane increased slightly after 7 days of the experiment and stabilized. The TP concentration of the upper water body increased compared with the lower water body at 21 days. At the end of the experiment, the upper and lower water bodies' TP concentration was 0.18 mg/L, respectively. 0.40mg/L.

The TP concentration in the upper and lower water bodies of experimental group B increased significantly in the first seven days of the experiment, then a downward trend, and then increased again on the 21st day. At the end of the experiment, the TP concentrations in the upper and lower water bodies were 0.49mg/L and 0.84mg/L. Anaerobic conditions in the blank group E and the experimental group D can accelerate the release of phosphorus in the sediments, resulting in a continuous increase in the TP concentration. The TP concentrations in the upper layers of all experimental groups were lower than those in the bottom layers. This is attributed to released phosphorus from the sedimentary layer to the water body. Besides, the TP concentration of the bottom layer of the blank group E was significantly higher than that of the upper layer, indicating that the fiber membrane has a certain mechanical blocking effect on phosphorus release.

Although the microorganisms in the experiment have no ability to remove total phosphorus, they can effectively inhibit the release of phosphorus in the bottom mud under LED light illumination and maintain the phosphorus concentration of the overlying water at a stable state. The microorganisms' metabolic activities can promote the release of phosphorus in the bottom mud, and the microorganisms can also absorb and assimilate the phosphorus in the water body to remove phosphorus(Lin et al., 2008; Song et al., 2013). However, as the number and activity status of microorganisms in the LED lighting group increases, the acid generated during the metabolism will dissolve the insoluble phosphate in the bottom mud, which promoted the release of phosphorus in the bottom mud. Since the rate of microbial absorption and assimilation and bottom sludge absorption is slower than the release rate, phosphorus concentration in the overlying water shows an upward trend. Since algal death in the red LED lamp group will also release phosphorus, the growth rate of the overlying water phosphorus is higher than the blue LED lamp group.

3.3 Overall

The primary function of fiber membrane is to provide attachment sites for the proliferation of microorganisms, which is more conducive to the formation of biofilms. Compared with the control group, the concentration of TN and TP in the lower layer of the fiber membrane in the fiber membrane group was significantly higher than that in the upper layer, indicating that the fiber membrane has a specific mechanical blocking effect on the release of nutrients in the bottom mud to the overlying water body.

There are also shortcomings in this study. There are differences between individuals in each experimental group, causing errors between each sampling, resulting in a significant degree of dispersion of data; covering the water surface cannot wholly make the water body in an anaerobic environment. It will also affect the experimental results. Make an impact. This study only evaluates whether LEDs are effective in improving eutrophic water bodies. A comprehensive evaluation of light intensity, light time, and microbial community changes is also needed in the follow-up. There will be a broader application prospect in the field of eutrophic water treatment and research.

Conclusions

(1) The blue and red LED light source can effectively increase the DO concentration of eutrophic water, and The blue LED light source obtained a better effect on increasing DO concentration to about 10mg/L, with that the properties of sediment have been significantly improved.

(2) Both the blue and red LED light sources increased the ORP value of the eutrophic water body and declined the NH_4-N concentration from 7mg/L to 1mg/L. Besides, both the blue and red LED light sources inhibited the release of phosphorus, and the inhibition effect of the blue LED light source was better than that of the red LED light source.

(3) Overall, the fiber membrane here mainly provides attachment sites for algae growth and mechanically blocks the release of nutrients to the upper water body. Its combination of the blue LED light source is more conducive to increasing the DO concentration with better remediation performance.

Declarations

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Contributions

Aimin Hao, Min Zhao and Yasushi Iseri developed the study design. Qi Mi, Kai He and Dong Xia performed the sampling and the analysis of water quality. Bingjun Liu, Yingchao Lin and Yongsi Zhu performed the statistical analyses and interpreted the findings. All authors contributed toward the writing and editing the manuscript. We confirm that this manuscript is in accordance with the Authorship statement of ethical standards for manuscripts submitted to Environmental Science and Pollution Research.

Ethics approval

This study was approved by the Wenzhou University, Sun Yat-sen University, and Nankai University which is indicated in the manuscript.

Consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare no competing interests.

Data availability

Not applicable

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Figures

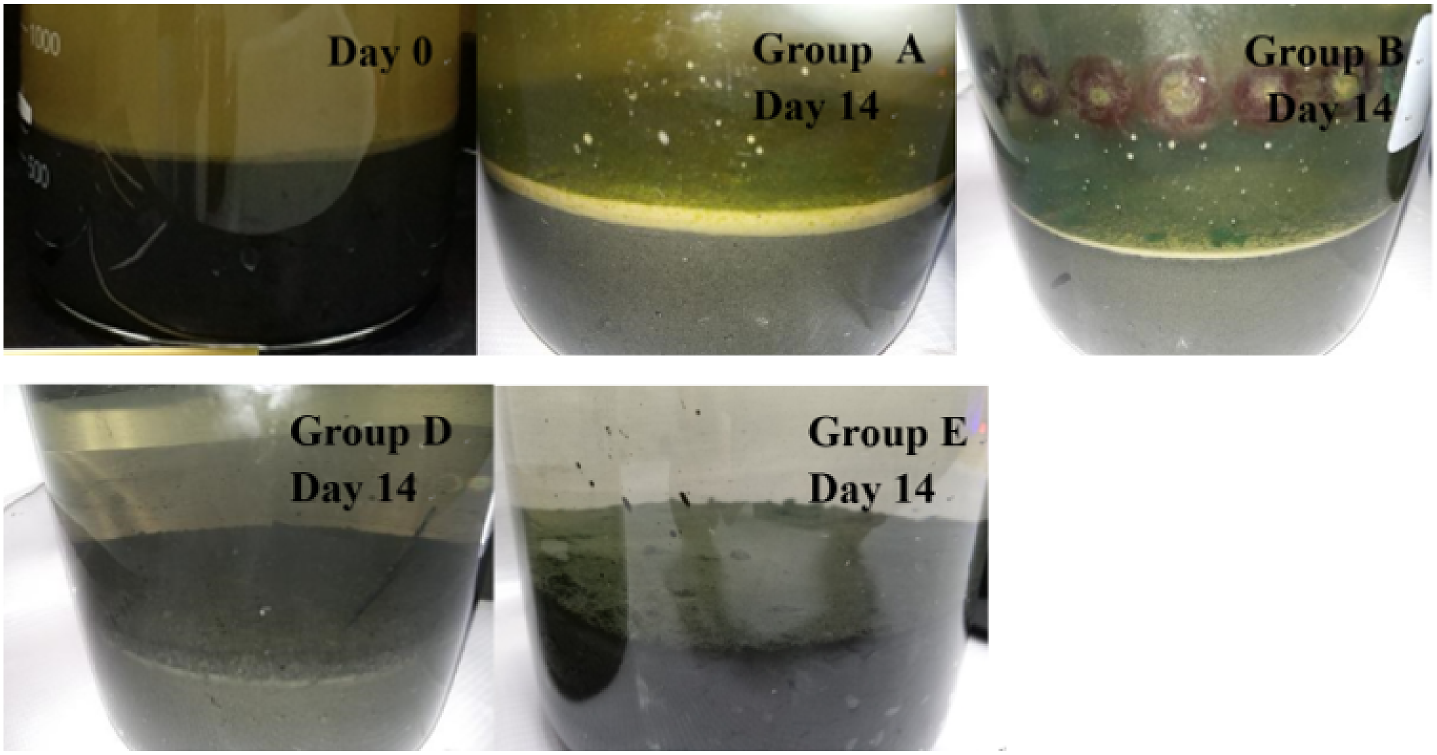

Figure 1

The apparent changes of sediments in different experimental groups

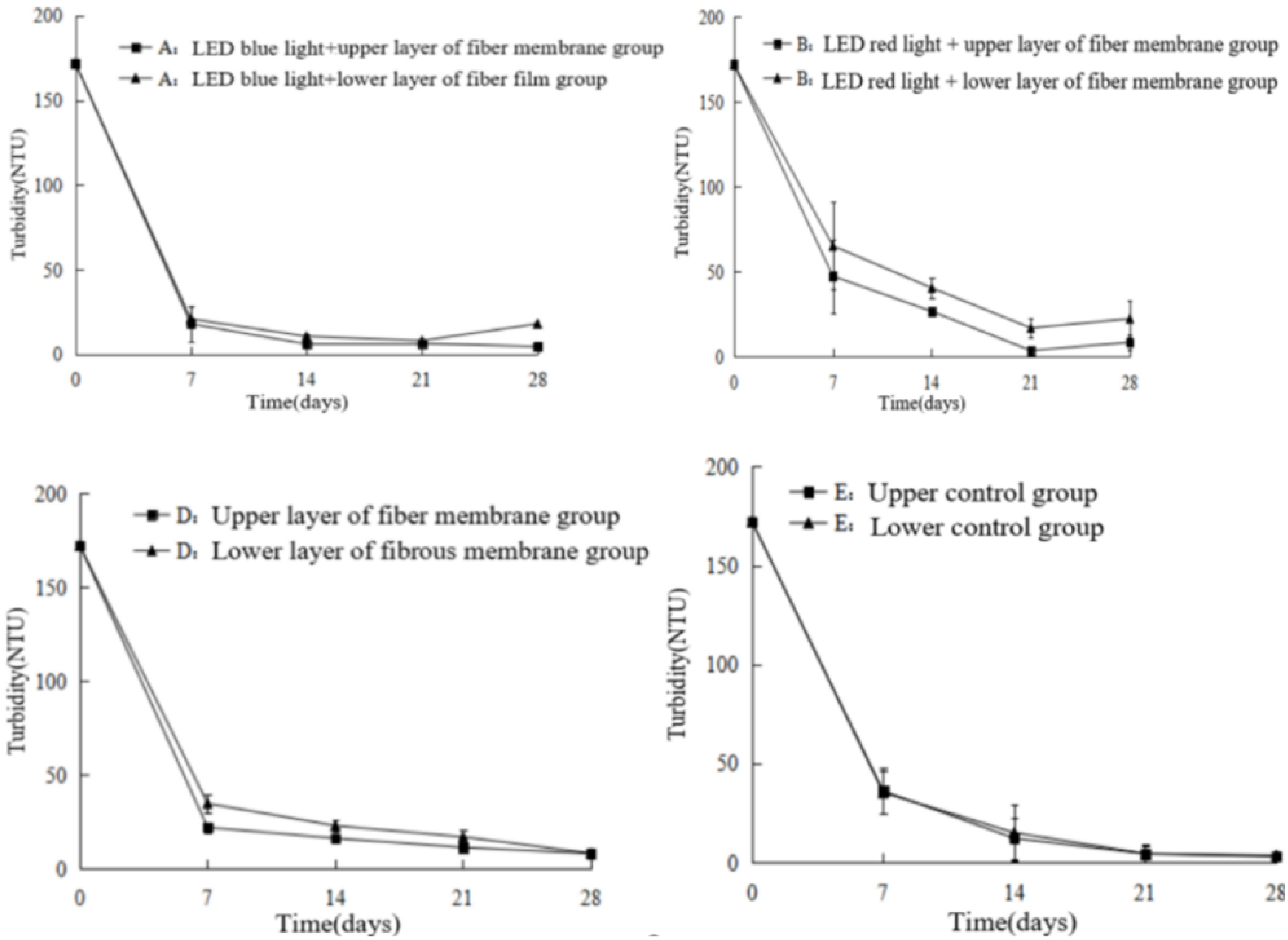

Figure 2

Changes in the turbidity of the upper and lower layers of LED fiber membranes of different colors

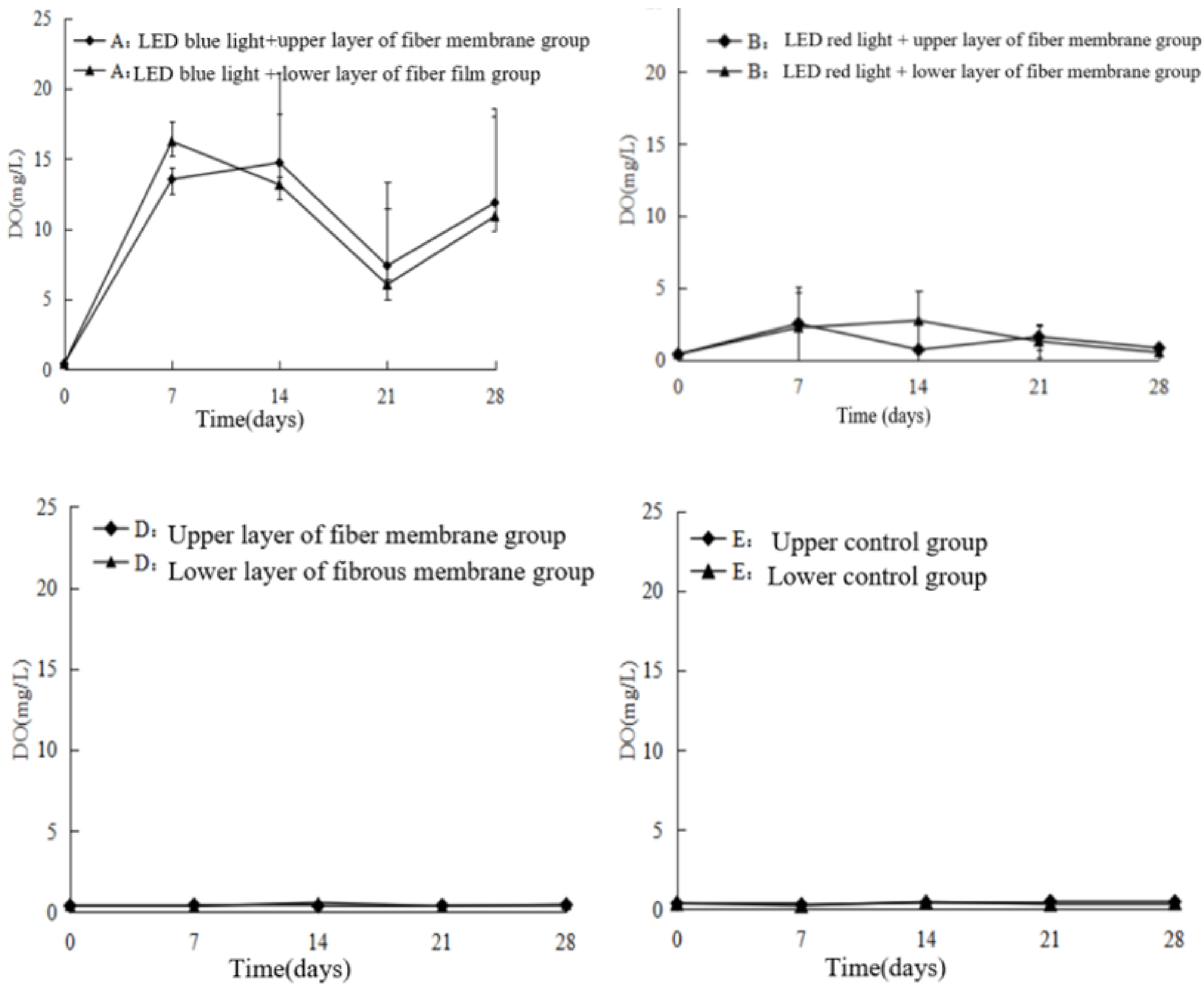

Figure 3

Changes of DO concentration in the upper and lower layers of LED fiber membranes of different colors

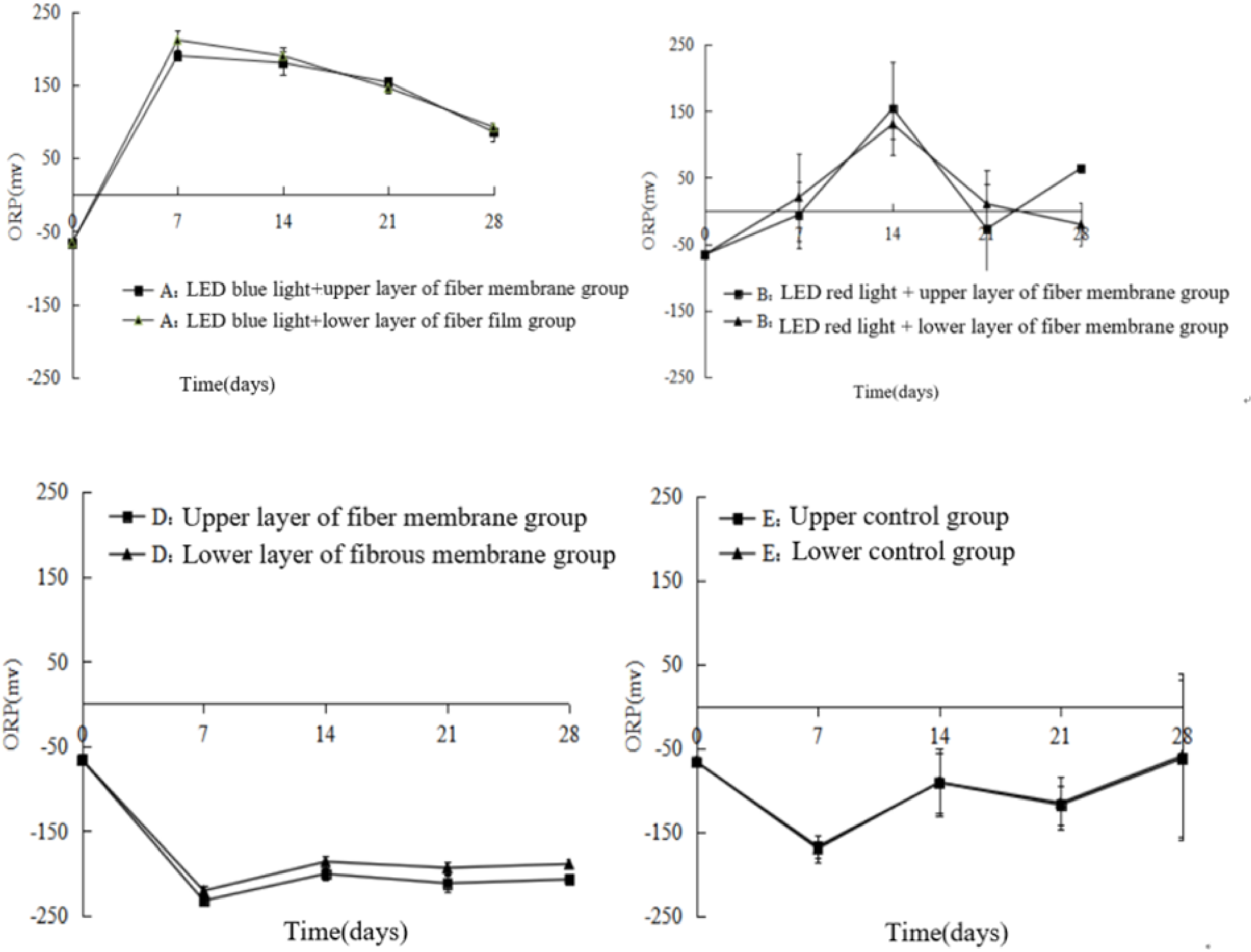

Figure 4

Changes in ORP values of the upper and lower layers of LED fiber membranes of different colors

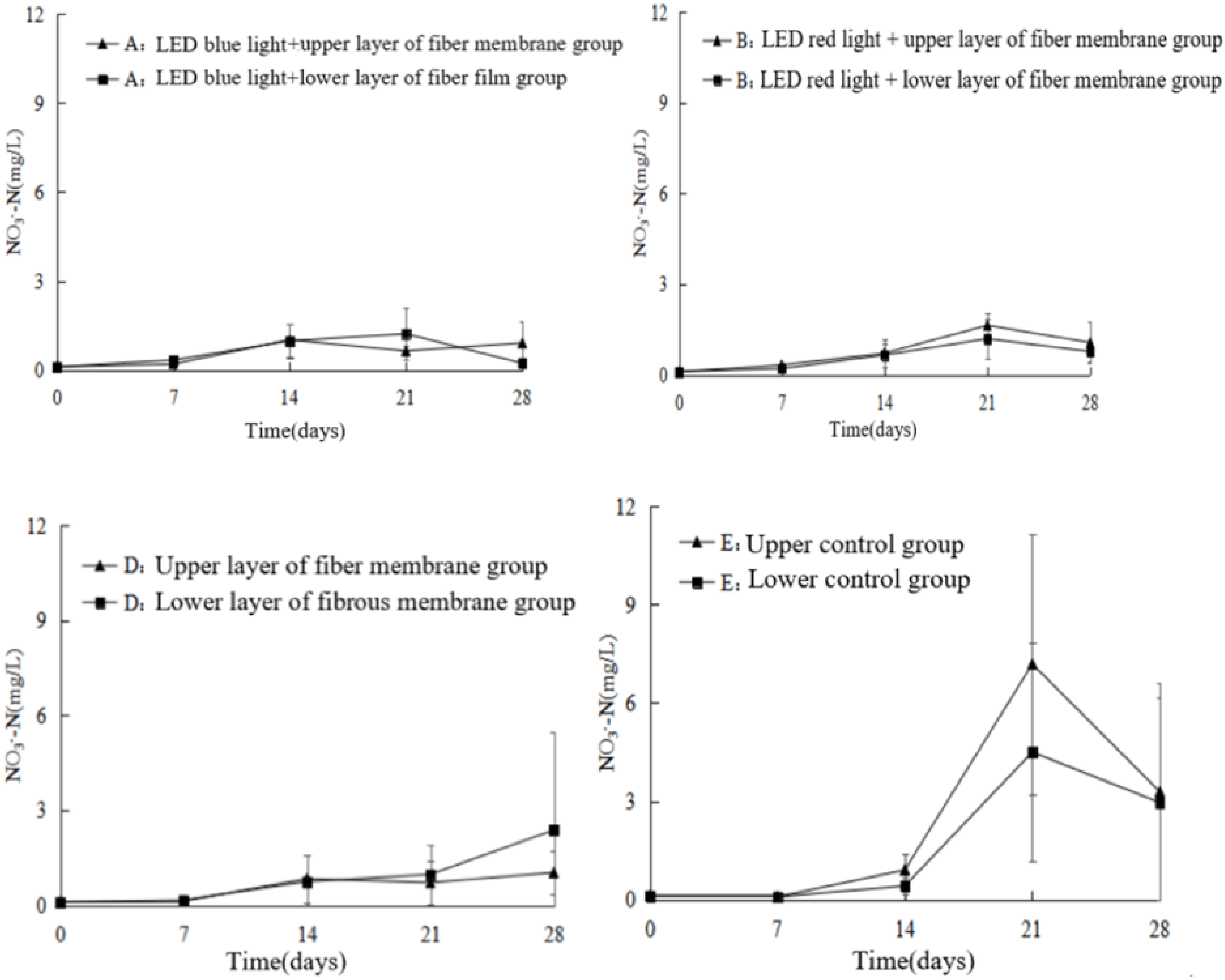

Figure 5

Changes of NO3–N concentration in the upper and lower layers of LED fiber membranes of different colors.

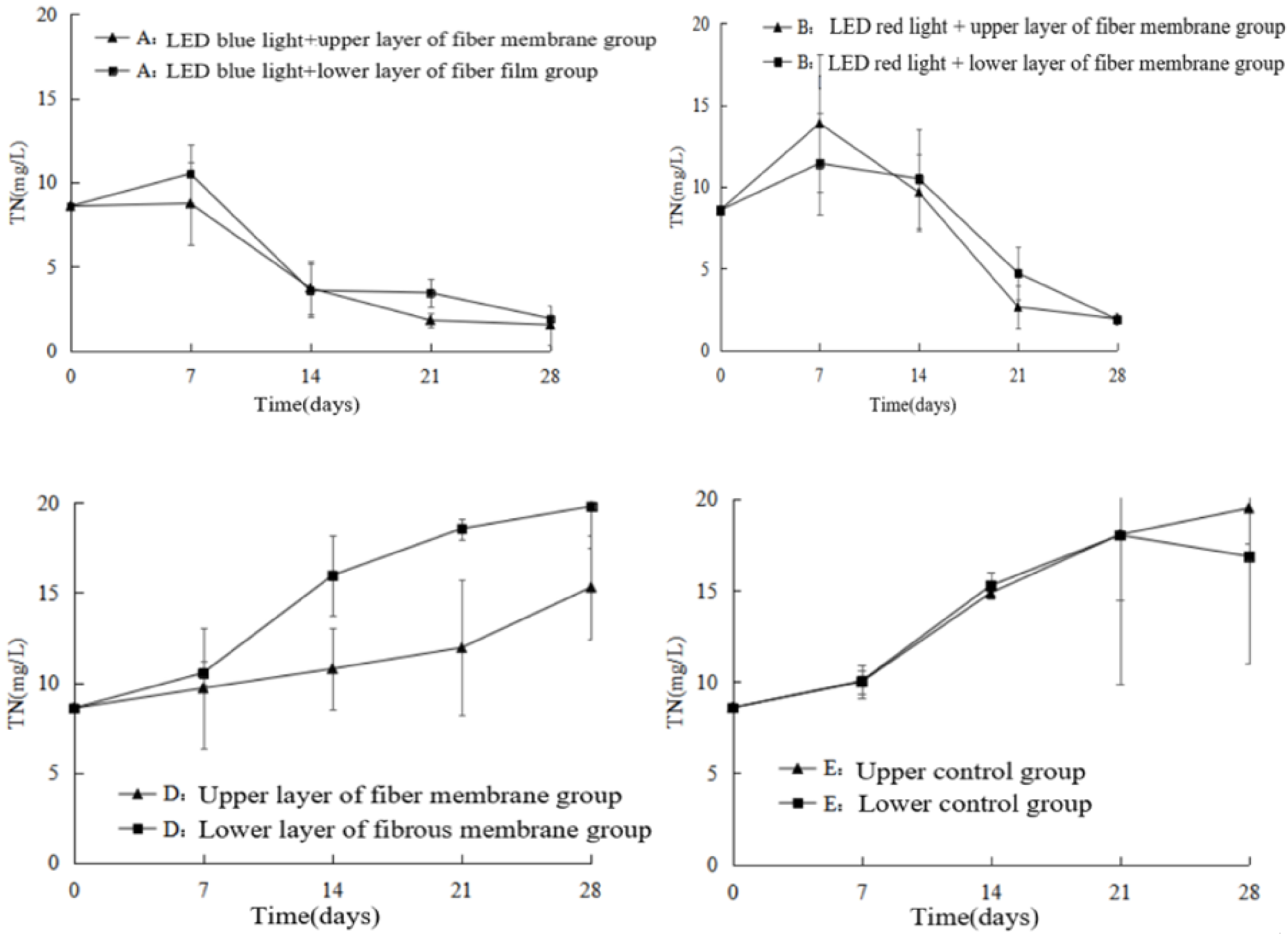

Figure 6

Changes of TN concentration in the upper and lower layers of LED fiber membranes of different colors

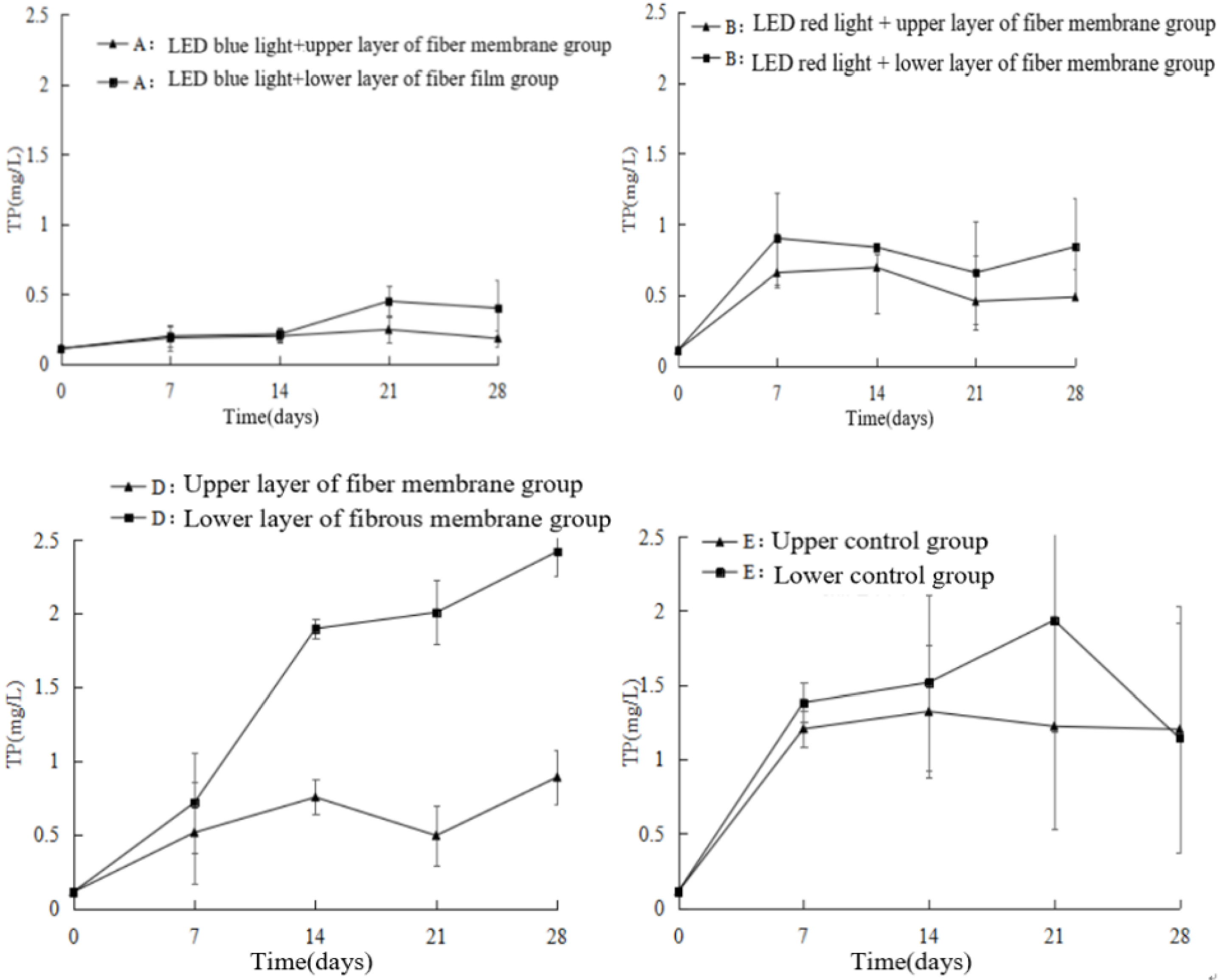

Figure 7

Changes of TP concentration in the upper and lower layers of LED fiber membranes of different colors

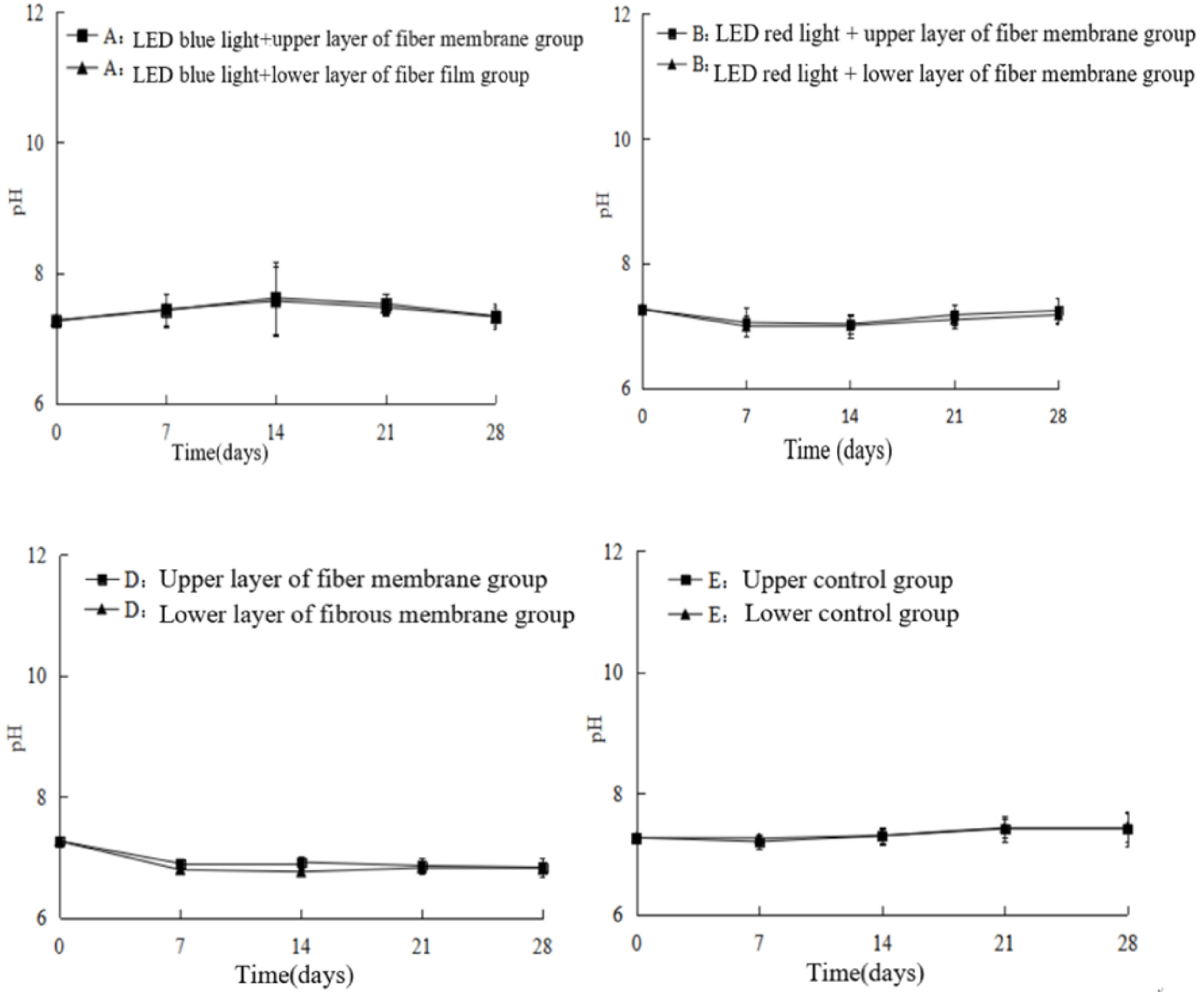

Figure 8

Changes in pH concentration of the upper and lower layers of different color LED fiber membranes

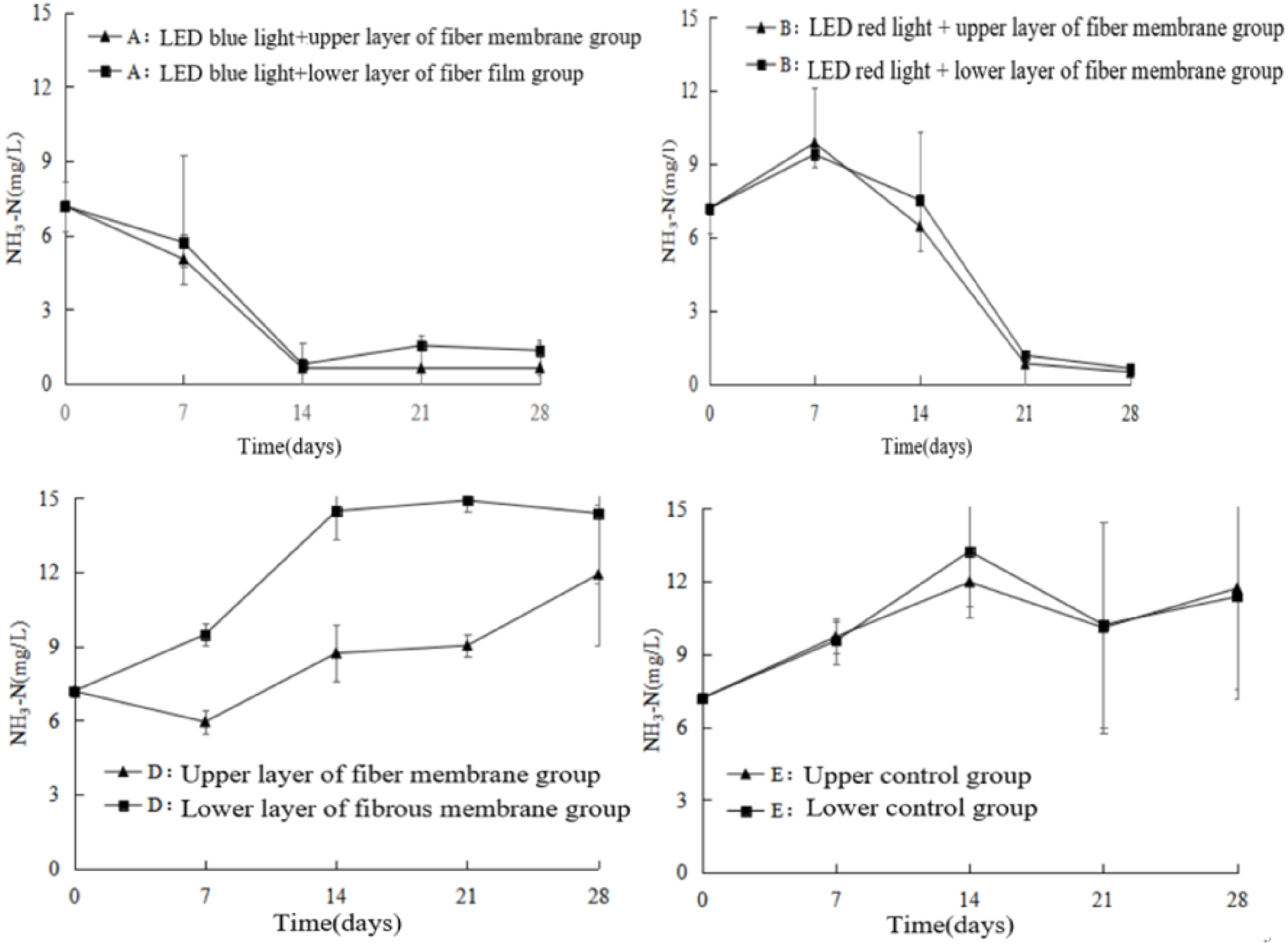

Figure 9

Changes in the concentration of NH4-N in the upper and lower layers of LED fiber membranes of different colors