Water Environmental Remediation in Organically Polluted Reservoir via Anoxification Recovery Using Underwater LED Irradiation

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（水中 LED 照射による無酸素化の解消を通じた有機汚濁貯水池の水環境修復）

区　　分　：甲

論 文 内 容 の 要 旨

In a reservoir with an excessive inflow of organic matter, a low transparency causes an anoxification in the deeper layer due to low dissolved oxygen (DO) levels in hot seasons. Anoxic water occurs not only because of inhibited oxygen production through phytoplankton photosynthesis under poor underwater light intensities, but also because of suppressed vertical transport of DO through thermal stratification. Anoxification leads serious environmental issues, such as the death of aquatic life because of oxygen deficiency, the pathogenic bacterial growth due to putrefaction of organic matter, the acceleration of eutrophic state by the elution of nutrients from the bottom sediment, the generation of toxic hydrosulfide, and the accumulation of sludge including metal sulfides and undecomposed organic matter on the bottom bed. Therefore, for the environmental conservation of water in organically polluted water bodies, it is important to develop effective counter measures against anoxification, and establish a technique to recover the anaerobic state.

This study focuses on a method for anoxification recovery using underwater light-emitting diode (LED) treatment in an organically polluted reservoir. Anoxification can be recovered by artificially improving the underwater light environment using an LED light source, and its effect is stemming from oxygen production via phytoplankton photosynthesis. In addition, this solution is linked to the improvement of water and bottom sediment environments with recovery from anaerobic to aerobic states. The objective of this study was to examine, at the laboratory level, how much RGB (red, green and blue) full-color underwater LED lamp irradiation would contribute to the water environmental remediation, by considering the influences of two factors, optical spectrum of light source and initial anaerobic condition of water, on the anoxification recovery. In this study, water quality parameters, such as DO, chlorophyll-a, dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphorous (DIP), were monitored via beaker and water tank experiments while using LED irradiation for 24 h (12 h on/12 h off) for 2 months in anoxic water, where the anaerobic decomposition of organic matter progressed under reductive conditions. The knowledge and outcomes acquired by the LED irradiation experiments can be summarized as follows from four viewpoints.

In single-color irradiations, having marginally sufficient photon intensity of approximately 50 μmol/(m^2 s), the green spectrum required more time to recover from the anoxic state because of the lower photosynthesis rate compared to the red and blue spectra. Additionally, the influence of oxygen production rate on the time required for the anoxification recovery was almost negligible between the red and blue spectra. In red and blue spectra, the equilibrium between nitrogen and phosphorous cycles for phytoplankton and nutrients was linked to a healthy DO level (more than 4 mg/L) without an overgrowth of phytoplankton; moreover, total nitrogen (TN) and total phosphorous (TP) concentrations decreased considerably because of the reductions in DIN and DIP. The red and blue spectra were essential to maintain a healthy DO level to ensure aquatic environmental conservation, although green spectrum irradiation played an auxiliary role for oxygen production via phytoplankton photosynthesis.

The photo-responsiveness and photosynthesis rate of phytoplankton could be enhanced in the presence of the green spectrum regardless of light intensity, and the anoxic state could be quickly recovered. In particular, LED irradiation with the three-color mixed RGB spectra (R:G:B=1:1:1) played an important role in promoting oxygen production compared to the mixed light of red and blue color spectra under low light intensity of approximately 20 μmol/(m^2 s). Under high intensity light of approximately 100 μmol/(m^2 s), DO rapidly increased to supersaturation after anoxification recovery due to the growth of green algae possessing high photosynthetic capacity regardless of the green spectrum. Also, LED irradiation, including the green color band, had an advantage such that the healthy DO environment was preserved without a decrease to poor oxygen levels in the absence of light. The water environmental remediation by solving the long-term anoxification under both strong and weak light intensity conditions were reflected in decreased TN and TP upon LED irradiation for 2 months. These results indicated the reduction of DIN and DIP through the aerobic matter cycle, in which phytoplankton played a leading role. In particular, phosphate formed a particulate inorganic chemical chelate with ferric ions generated by the oxidation of ferrous ions after recovering the anaerobic condition, resulting in the reduction of TP. Water environmental remediation by recovery formed anaerobic state to aerobic includes the inhibition of PO_4-P and NH_4-N elution from the sediment.

Although the light intensity of approximately 10 μmol/(m^2 s) was one-tenth of the lower limit of the optimum photon intensity required for photosynthesis, the anoxic state was finally improved to a healthy DO level. Such an effective improvement in the DO level was attributed to the equilibrated biochemical balance between the oxygen consumption during photosynthesis and oxygen supply into the water due to respiration and mineralization, regardless of the initial anaerobic conditions. However, the initial anaerobic condition influenced the oxygen production rate. The LED irradiation under high initial nutrient concentrations stemming from long-term anoxification would be advantageous regarding the time required to reach a healthy DO level, average increasing DO rate, and maximum and stable concentrations. The oxygen production rate promoted by the initial high concentrations of NH_4-N and PO_4-P were associated with the early recovery of anoxification despite the high oxygen consumption due to the presence of many oxidative substances. In addition, the rapid increase in the DO level to a saturated state due to increased oxygen production rate produced NO_3-N due to the aerobic decomposition of organic matter and the oxidation of NH_4-N. Further, the increase in NO_3-N weakened the initial strong nitrogen-limitation state required for phytoplankton photosynthesis. Consequently, a high supply of nutrients was associated with a healthy DO environment.

Under extremely weak light intensity of approximately 5 μmol/(m^2 s), which was one-twentieth of the optimum photon intensity, the photosynthesis rate decreased considerably due to the strong limitation of light linked to marginal oxygen production, which was significantly less than the oxygen consumed for oxidizing a large proportion of the oxidative substances. Consequently, the anoxic state could not be recovered despite the LED irradiation. However, the minimum effects of water environmental remediation were observed wherein the marginal oxygen production could restrict water quality degradation due to the anaerobic reductive reactions.

This study indicates the spatial effect of water environmental remediation via LED irradiation was not limited to the vicinity of the light source but was applicable to a wide range, in which the light intensity contributed to one-twentieth of the optimum photon intensity for phytoplankton photosynthesis. All of those results could be used to design optimal LED irradiation techniques to mitigate anoxification to sustain a healthy aquatic environment.