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Effect of ultraviolet radiation on nitrogen and phosphorus removal from sewage in plateau environment

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ABSTRACT

The high-altitude conditions provide an appropriate environment for research. Through the self-made reactor, the power of the ultraviolet lamp, the distance from the liquid surface and the irradiation time are control parameters, and the ultraviolet lamp is utilized to remove pollutants. The research results of the study indicate that the optimal conditions for removal of chemical oxygen demand (COD), total nitrogen (TN), ammonia nitrogen (NH_4^+–N) and total phosphorus (TP) by ultraviolet radiation are, respectively, 15-W UV lamp, 0.5 min of irradiation time, 10 cm of irradiation distance, and 18 W, 1 min, 20 cm, and 20 W, 5 min, 20 cm, and 15 W, 3 min, 5 cm. The effect of ultraviolet radiation on the removal of four pollutants is ranked as TN > TP > COD > NH_4^+–N. It is further recommended that the sewage treatment plant set the conditions of 15-W UV lamp, 5 min of irradiation time and 5 cm of irradiation distance.

Keywords: Nitrogen and phosphorus removal; Ultraviolet radiation; Optimal removal rate; Different working conditions; Plateau environment

1. Introduction

Tibet, a plateau in the world, whose average altitude exceeds 4,000 m [1], is known as the "roof of the world" and the world's last pure land in the world. Special environments such as low temperature, strong ultraviolet rays, and low dissolved oxygen are the main characteristics of plateau areas, which severely restrict wastewater discharge. Organic pollutants such as chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) in sewage are the main indicators that affect the quality of sewage. The research achieved by many scholars show that ultraviolet radiation has different effects on organic pollutants, bacteria and viruses, water environment, plankton, etc. [2–7].

The UV radiation intensity of the lamp is mainly related to three working conditions namely the lamp power, irradiation time and irradiation distance [8], but the conclusions of the scholars on the removal of microorganisms vary under different working conditions. For example, ultraviolet disinfection and sterilization conform to the first-order photobiochemical reaction dynamic relationship, and its effect is positively correlated with UV radiation intensity and irradiation time [9,10]. And studies have shown that the law of removing microorganisms by ultraviolet radiation does not conform to the same level of dynamic relationship [11,12]. The research results of Guo et al. [13] and Bohrerova and Linden [14] showed that the removal effect of UV radiation on microorganisms is related to irradiation distance and irradiation time, instead of the power of the lamp. The mechanism of ultraviolet radiation for nitrogen and phosphorus removal in sewage mainly promotes or inhibits nitrifying bacteria, phosphorus accumulating bacteria and denitrifying bacteria [15] to stimulate the removal of nitrogen and phosphorus from sewage. Compared with other processes, the use of ultraviolet radiation for wastewater

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treatment has the advantages of low energy consumption, low cost, and easy management.

There are few studies on nitrogen and phosphorus removal from sewage in plateau areas, and treating UV radiation intensity as an influencing factor is still at a blank stage. In order to better study the effect of lamp power, irradiation time and irradiation distance on the removal of nitrogen and phosphorus in sewage, this paper takes three working conditions as the influencing factors of ultraviolet radiation intensity to explore the best removal rate and the corresponding optimal working conditions.

2. Materials and methods

The sewage in the septic tank of Tibet Agriculture and Animal Husbandry University at 29°40′0″ north latitude, 94°20′30″ east longitude, and 2,996.2 m above sea level was used as the sample to test, and the ultraviolet lamp was used to treat the sewage through a self-made reactor. The self-made reactor is made of transparent acrylic plate and has a rectangular parallelepiped shape. It is 20 cm long, 10 cm wide and 65 cm high. As shown in Fig. 1, three working conditions are set as follows: lamp power, irradiation duration and irradiation distance. The wavelength of the ultraviolet lamp is 253.7 nm, which belongs to the C-band of ultraviolet [16]. The length of 10-, 15-, 18- and 20-W UV lamp is 331, 436, 550 and 589 mm, respectively. The irradiation time is 0.5, 1, 2, 3 and 5 min, and the height from the liquid surface is 5, 10 and 20 cm, respectively.

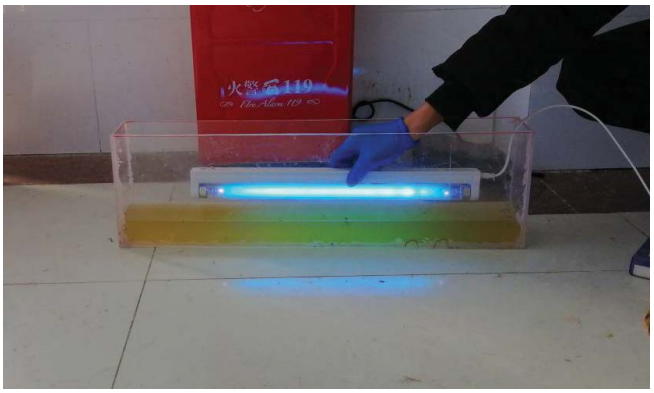

Fig. 1. Physical picture of the process of ultraviolet radiation on sewage treatment.

The test applies the control variable method to keep the two working conditions unchanged, and only change the remaining one factor. Sewage from the septic tank was poured into a water bucket, allowed to settle in the water bucket for 10 min, then poured into the reactor, and irradiated under different working conditions. The measurement mainly affects the concentration of the four indicators of sewage water quality so as to find the removal rate, and obtain the specific working conditions when the removal effect is the best. The analysis methods of water quality indicators such as COD, TN, ammonia nitrogen (NH_4^+–N) and TP are shown in Table 1.

The sewage before irradiation was taken as the raw water sample, and the concentration of the corresponding index was measured. The concentration range and average value are shown in Table 2, and the unit in the table is mg/L.

The minimum discharge concentration of sewage COD, TN and NH_4^+–N in the septic tanks of Tibet Agriculture & Animal Husbandry University has not reached the standards for the discharge of pollutants of urban sewage treatment plants [17], and some of the TP discharge concentration has reached the second and third level standards.

3. Results

3.1. Effect of UV radiation on COD removal

The lamp power, irradiation time and irradiation distance were controlled separately to study the effect of ultraviolet radiation on COD removal. Through the origin, taking the irradiation time as the abscissa, the lamp power as different curve, and the COD removal rate as the ordinate, a spline curve diagram was established, and three spline curve diagrams with irradiation distances of 5, 10 and 20 cm were obtained. For the observation and horizontal

Table 1
Analysis method of water quality index

Water quality index	Analytical method
COD	Potassium dichromate oxidation digestion spectrophotometry
TN	Potassium persulfate-digestion ultraviolet spectrophotometry
NH_4^+–N	Distillation and titration
TP	Ammonium molybdate spectrophotometry

Table 2
Concentration range and average value of corresponding indicators in raw water samples

	COD	TN	NH_4^+–N	TP
Concentration range	360.92–537.29	80.95–170.85	81.98–203.5	2.1–8.98
Average value	420.2	117.89	144.71	5.0

and vertical analysis, the three diagrams are combined to obtain a diagram of the effect of UV radiation on COD removal, as shown in Fig. 2.

Analysis of the irradiation distance of 5 cm: the 18-W UV lamp has little effect on the removal effect of COD, and the removal rate of COD is 3.47%–8%. When the irradiation time is 3 min, the removal rate of COD is 8% at the most. When the UV lamp is 20 W, the removal rate of COD shows a trend of rising first, then falling and then rising. When the irradiation time is 2 min, the maximum COD removal rate is 15.1%. When the lamp is 10 and 15 W, the removal rate of COD shows a trend of increasing first and then decreasing. When the irradiation time of both is 3 min, the removal rate of COD is the highest. The former is 25.18%, the latter is 27.91%. When the irradiation time is 0.5 min, the removal rate of COD among the four is the lowest. When the irradiation distance is 5 cm, the lamp tube is 15 W, and the irradiation time is 3 min, the removal rate of COD can be maximized.

Analysis of the irradiation distance of 10 cm: the 20-W UV lamp has little effect on the removal effect of COD, and the removal rate of COD is 5.22%–9.08%. When the irradiation time is 2 min, the removal rate of COD is up to 9.08%. When the tube is 10 and 20 W, the removal rate of COD shows a trend of increasing first and then decreasing. When the former irradiation time is 2 min, the removal rate of COD is up to 13.05%. When the irradiation time of the latter is 5 min, the removal rate of COD is 14.3% at the most. When the UV lamp is 15 W and the irradiation time is 0.5 min, the removal rate of COD is the highest, which is 30.82%. When the irradiation distance is 10 cm, the UV lamp is 15 W, and the irradiation time is 0.5 min, the removal rate of COD can be maximized, which is 2.91% higher than the working condition under the irradiation distance of 5 cm.

Analysis of the irradiation distance of 20 cm: when the UV lamp is 20 W, the removal rate of COD shows a trend of decreasing first and then increasing. When the irradiation time is 5 min, the maximum COD removal rate is 13.18%. When the UV lamp is 10 W, the removal rate of COD shows a trend of increasing first and then decreasing. When the irradiation time is 1 min, the removal rate of COD is 13.08% at the maximum. When the UV lamp is 18 W, the removal rate of COD basically shows an upward tendency. When the irradiation time is 5 min, the maximum COD removal rate is 12.18%. When the UV lamp is 15 W, the removal rate of COD shows a trend of rising first, then falling, then rising and finally falling. When the irradiation time is 3 min, the removal rate of COD is the highest, up to 21.79%. When the irradiation distance is 20 cm, the UV lamp is 15 W, and the irradiation time is 3 min, the removal rate of COD can be maximized, which is 6.12% lower than the working condition of the irradiation distance of 5 cm.

Overall, the UV lamp of 15 W has a better effect on COD removal. The irradiation time of 3 and 5 min has a better effect on COD removal. When the COD removal effect is the best, no better irradiation distance can be obtained. The best working condition for COD removal is the UV lamp of 15 W, irradiation time of 0.5 min and irradiation distance of 10 cm, and the COD removal rate is 30.82%.

3.2. Effect of UV radiation on TN removal

In the same way as in section 3.1, the effect of UV radiation on TN removal is shown in Fig. 3.

Analysis of the irradiation distance of 5 cm: UV lamp of 15 W has a significant effect on the removal effect of TN, the removal rate of TN is between 7.37% and 45.41%. When the irradiation time is 3 min, the maximum removal rate of TN is 45.41%. When the UV lamp is 18 and 20 W, the removal rate of TN basically shows an upward trend. When the former irradiation time is 3 min, the maximum removal rate of TN is 23.17%. When the latter irradiation time is 5 min, the maximum removal rate of TN is 28.06%. When the UV lamp is 10 W, the removal rate of TN shows a trend of rising first and then decreasing and then rising. The removal rate of TN is 8.6%–42.05%. When the irradiation time is 5 min, the maximum removal rate of TN is 42.05%. When the irradiation time is 0.5 min, the removal rate of TN by the four of them was the lowest, and none of them exceeded 10%. When the irradiation distance is 3 and 5 cm, the removal rate of TN among the four is the highest. When the removal rate of TN reaches the maximum value, the corresponding UV lamp is 15 W, and the irradiation duration is 3 min.

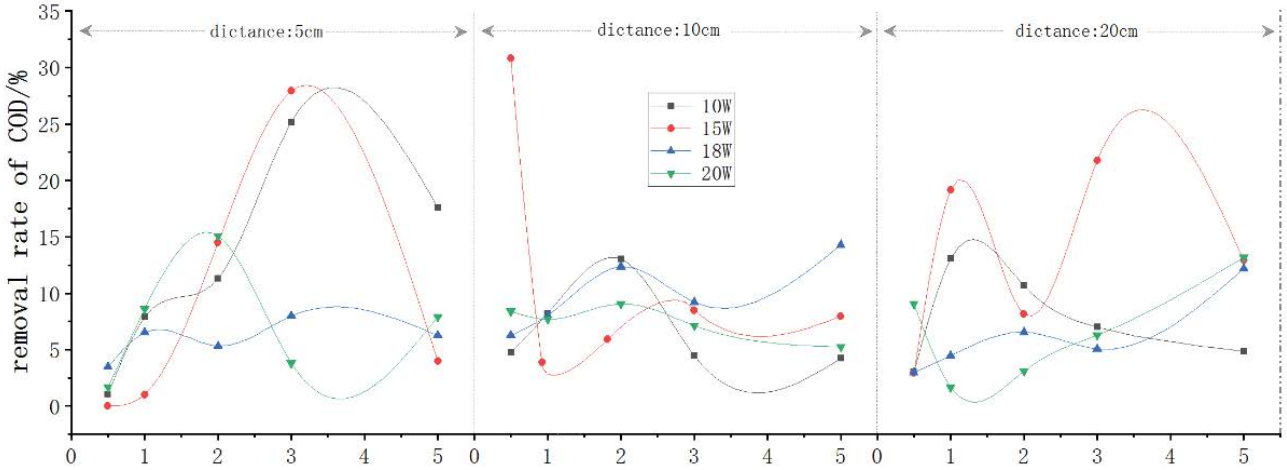

Fig. 2. Effect of UV radiation on COD removal.

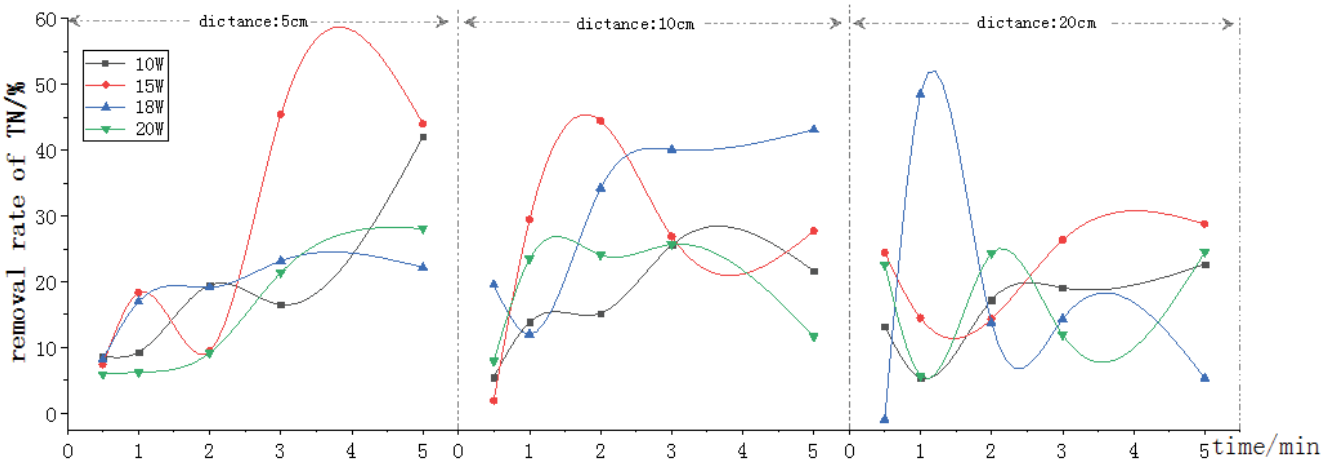

Fig. 3. Effect of UV radiation on TN removal.

Analysis of the irradiation distance of 10 cm: when the UV lamp is 10 W, the removal rate of TN shows an upward trend and then a downward trend, and the removal rate of TN is 5.45%–25.57%. When the irradiation time is 3 min, the maximum removal rate of TN is 25.57%. The removal effect of 15-W UV lamp on TN is obvious, and the removal rate of TN is 1.91%–44.47%. When the irradiation time is 2 min, the maximum removal rate of TN is 44.47%. When the UV lamp is 18 W, the removal rate of TN shows a tendency of decreasing first and then increasing. When the irradiation time is 1 min, the minimum removal rate of TN is 11.94%. When the irradiation time is 5 min, the maximum removal rate of TN is 43.09%. When the UV lamp is 20 W, the removal rate of TN shows a trend of increasing first and then decreasing. When the irradiation time is 3 min, the maximum removal rate of TN is 25.69%. When the removal rate of TN reaches the maximum, the corresponding UV lamp is 15 W, and the irradiation duration is 2 min. It is nearly 1% lower than the working condition with an irradiation distance of 5 cm.

Analysis of the irradiation distance of 20 cm: the effect of the 18-W UV lamp on the removal effect of TN is more obvious. When the irradiation time is 1 min, the removal rate of TN is 48.52%. When the UV lamp is 20 W, the removal rate of TN is 5.68%–24.5%. When the irradiation time is 5 min, the maximum removal rate of TN is 24.5%. When the UV lamp is 15 W, the removal rate of TN shows a trend of decreasing first and then increasing. The removal rate of TN is 14.3%–28.78%. When the irradiation time is 5 min, the maximum removal rate of TN is 28.78%. When the UV lamp is 10 W, the removal rate of TN shows a trend of decreasing first and then increasing. The removal rate of TN is 5.36%–22.62%. When the irradiation time is 5 min, the removal rate of TN is the highest, up to 22.62%. When the irradiation distance is 20 cm, the lamp is controlled to 18 W and the irradiation time to 1 min, the removal rate of TN can be maximized, which is 3.1% higher than the working condition under the irradiation distance of 5 cm.

Overall, the effect of ultraviolet radiation on TN removal is better, and the optimal removal rate is nearly 50%, which is 17.7% higher than the optimal removal rate of COD. The irradiation time of 3 and 5 min has a better effect on the removal of TN, the irradiation distance has a greater influence on the removal effect of TN, and no better irradiation distance has been obtained. The best working condition for TN removal is UV lamp of 18 W, irradiation time of 1 min and irradiation distance of 20 cm.

3.3. Effect of UV radiation on NH_4^+–N removal

In the same way as above, the effect of UV radiation on NH_4^+–N removal is obtained, as shown in Fig. 4.

Analysis of the irradiation distance of 5 cm: the removal effect of 20-W UV lamp on NH_4^+–N is poor, and the removal rate is lower than other working conditions. When the irradiation time is 2 min, the removal rate of NH_4^+–N is 4.09% at the maximum. The UV lamp of 18 W has a great influence on the removal effect of NH_4^+–N, and the removal rate is between 4.08% and 14.55%. When the irradiation time is 5 min, the removal rate of NH_4^+–N is 14.55% at the maximum. When the UV lamp is 15 W, the removal rate of NH_4^+–N shows an upward trend, the removal rate is between 3.64% and 9.27%. When the UV lamp is 10 W, the removal rate of NH_4^+–N shows a trend of decreasing first and then increasing, and the removal rate is between 4.75% and 10.84%. When the irradiation time is 5 min, the removal rate of NH_4^+–N is up to 10.84%. When the irradiation distance is 5 cm, the removal rate of NH_4^+–N among the three is the largest. When the removal rate reaches the maximum, the corresponding UV lamp is 18 W, and the irradiation time is 5 min.

Analysis of the irradiation distance of 5 cm: the removal effect of 20-W UV lamp on NH_4^+–N is poor, and the removal rate is lower than other working conditions. When the irradiation time is 2 min, the removal rate of NH_4^+–N is 4.09% at the maximum. The UV lamp of 18 W has a great influence on the removal effect of NH_4^+–N, the removal rate is between 4.08% and 14.55%. When the irradiation time is 5 min, the removal rate of NH_4^+–N is 14.55% at the maximum. When the lamp is 15 W, the removal rate of NH_4^+–N shows an upward trend, the removal rate is 3.64%–9.27%. When the UV lamp is 10 W, the removal rate of NH_4^+–N

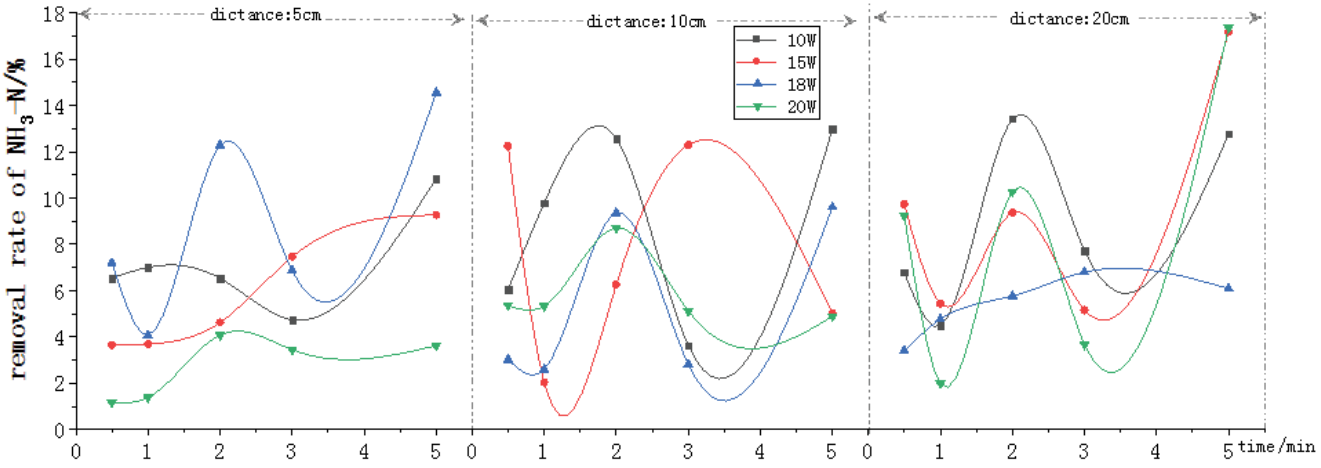

Fig. 4. Effect of UV radiation on NH_4^+–N removal.

shows a trend of decreasing first and then increasing, and the removal rate is 4.75%–10.84%. When the irradiation time is 5 min, the removal rate of NH_4^+–N is up to 10.84%. When the irradiation distance is 5 cm, the removal rate of NH_4^+–N among the three is the largest. When the removal rate reaches the maximum, the corresponding UV lamp is 18 W, and the irradiation time is 5 min.

Analysis of the irradiation distance of 20 cm: The UV lamp of 18 W has little effect on the removal effect of NH_4^+–N, the removal rate is between 3.42% and 6.8%. When the irradiation time is 3 min, the removal rate of NH_4^+–N is up to 6.8%. When the UV lamp is 20 W, the removal rate of NH_4^+–N is 1.99% and 17.36%. When the irradiation time is 5 min, the removal rate of NH_4^+–N is 17.36% at the maximum. When the UV lamp is 15 W, the removal effect of NH_4^+–N changes significantly, and the removal rate is 5.15%–17.18%. When the irradiation time is 5 min, the removal rate of NH_4^+–N is 17.18% at the maximum. When the UV lamp is 10 W, the removal rate of NH_4^+–N is 4.49%–12.76%. When the irradiation time is 2 min, the removal rate of NH_4^+–N is up to 12.76%. When the power of the UV lamp is 10, 15 and 18 W, the NH_4^+–N removal rate changes at the same way, with a trend of decreasing first, then increasing, decreasing after that and increasing finally. When the UV lamp is 20 W and the irradiation time is 5 min, the removal rate of NH_4^+–N can be maximized, which is 2.81% higher than the working condition with the irradiation distance of 5 cm.

Overall, the irradiation time of 5 min has a better removal effect on NH_4^+–N, and the best removal conditions are 20 W, 5 min, 20 cm. The effect of ultraviolet radiation on the removal of NH_4^+–N is not good, and the best removal rate is only 17.36%. The optimal removal rate is 13.46% lower than COD and 31.16% lower than TN.

3.4. Effect of UV radiation on TP removal

In the same way as above, the effect of UV radiation on TP removal is obtained, as shown in Fig. 5.

Analysis of the irradiation distance of 5 cm: the UV lamp of 10 W has a greater influence on the removal effect of TP; the removal rate is –6.18% to 26.02%. When the irradiation time is 3 min, the maximum removal rate of TP is

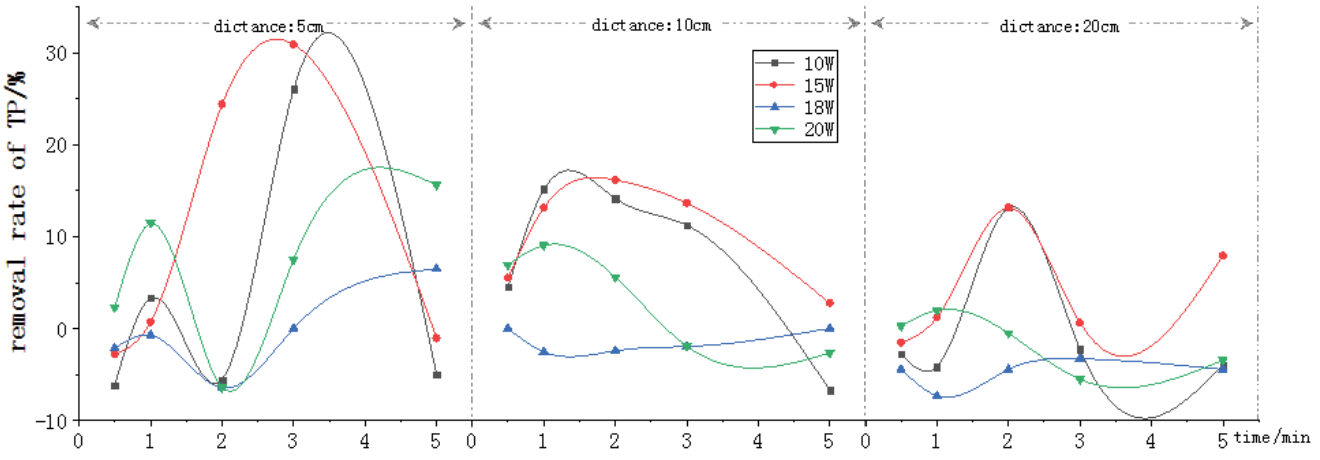

Fig. 5. Effect of UV radiation on TP removal.

26.02%. When the UV lamp is 15 W, the removal rate of TP increases first and then decreases, and the removal rate is –2.81% to 30.89%. When the irradiation time is 3 min, the maximum removal rate of TP is 30.89%. The UV lamp of 18 W has a poor influence on the removal effect of TP, and the removal rate is –6.47 to 6.47%. When the irradiation time is 5 min, the maximum removal rate of TP is 6.47%. When the UV lamp is 20 W, the removal rate of TP is –6.42 to 15.6%. When the irradiation time is 5 min, the maximum removal rate of TP is 15.6%. When the TP removal effect is better, the corresponding irradiation distance is 3 and 5 cm, and the corresponding lamp tube is 10 and 15 W. When the removal effect is optimal, the corresponding UV lamp is 15 W and the irradiation duration is 3 min.

Analysis of the irradiation distance of 10 cm: when the UV lamp is 10 and 15 W, the removal rate of TP showed a trend of increasing first and then decreasing. When the irradiation time of the former is 2 min, the maximum removal rate is 15.15%, and when the irradiation time of the latter is 3 min, the maximum removal rate is 16.16%. The removal effect of 18-W UV lamp on TP is unsatisfactory, the change is not obvious, and the removal rate is –2.56% to 0. When the UV lamp is 20 W, the removal rate of TP shows a trend of increasing first and then decreasing, the removal rate is –2.66% to 9.03%. When the irradiation time is 2 min, the maximum removal rate of TP is 9.03%. When the removal effect of TP is better, the corresponding irradiation distance is 2 and 3 cm, and the corresponding UV lamp is 10 and 15 W. When the removal effect is optimal, the corresponding UV lamp is 15 W and the irradiation duration is 2 min. It is 14.73% lower than the working condition with an irradiation distance of 5 cm.

The analysis of the irradiation distance of 20 cm: when the UV lamp is 10 and 15 W, the trend of TP removal rate is similar, which is basically the trend of first rising and then falling and then rising. When the irradiation time of both is 2 min, the removal rate is 13.13% at the maximum. The UV lamps of 18 and 20 W have a poor removal effect on TP, and the change is not obvious. When the irradiation time of the former is 3 min, the maximum removal rate is –3.3%, and when the irradiation time of the latter is 1 min, the maximum removal rate is 1.98%. When the corresponding lamps are 10 and 15 W, the removal effect of TP is better, and when the corresponding lamps are 10 and 15 W, and the irradiation time is 2 min the removal effect is optimal. 3.03% lower than the working condition with an irradiation distance of 10 cm.

Overall, 10 and 15 W lamps have better removal effect on TP, and when the distance is 5 cm the removal effect is better than that of 10 and 20 cm. When conditions are set to be 15 W, 3 min and 5 cm, the removal effect is the best. The effect of ultraviolet radiation on the removal of TP is not good because although the optimal removal rate is 30.98%, half of the working conditions have a negative value and 0 for TP. The optimal removal rate was 0.16% lower than COD, 17.54% lower than TN, and 13.62% higher than NH_4^+–N.

4. Discussions

Xiang et al. [18] used a 20-W ultraviolet lamp to irradiate the activated sludge, and the irradiation time was controlled to be 0.5, 3, 5, 10 and 15 min. As indicated from the result, the time corresponding to the best removal effect of TP was 0.5 min, an increase to 8% from 4% before radiation. When the corresponding working conditions are 15 W, 3 min and 5 cm, TP can be best removed. Zheng et al. [19] and others used a 30-W UV lamp for irradiation at a distance of 20 cm for a stay of 20 s, 40 s and 1 min, respectively, to detect the removal rate of COD in sewage. The results of the study showed that the COD removal rate reached the maximum when the time was 40 s, and the COD strain died when the time was 1 min. When the corresponding irradiation distance is 10 cm, the lamp is 15 W, and the irradiation time is 0.5 min, the COD can be best removed in this study. In general, the COD removal effect is better when the irradiation time is 3 min. Wang [20] used a 20-W UV lamp 20 cm away from the upper sludge, and controlled the radiation time to 20, 40, 60 and 80 s. The results show that the radiation time corresponding to the best COD and TN treatment effect is 40 s, the radiation time corresponding to the best TP treatment effect is 20 and 40 s, and the radiation time corresponding to the best NH_4^+–N treatment effect is 60 s. In this experiment, when the ultraviolet lamp is 20 W and the radiation distance is 20 cm, the radiation time corresponding to the best COD, TN and NH_4^+–N removal effect is 5 min, and the radiation time corresponding to the best TP removal effect is 0.5 min.

In summary, because UV radiation can reduce the concentration of TN and NH_4^+–N, it curbs the growth and reproduction of denitrifying flora and nitrobacteria, to some extent. Since the removal rate of TN is greater than that of NH_4^+–N, denitrifying flora are more sensitive to UV radiation than nitrobacteria. When different working conditions are set, the concentration of TP increased and then decreased, which indicated that UV radiation inhibited the growth and reproduction of phosphorus accumulating organisms (PAOs) and none phosphorus accumulating bacteria (NPAB). Because the positive value of the removal rate of TP is greater than the negative value, PAOs are more sensitive to NPAB against ultraviolet radiation. According to the comparison of nitrogen and phosphorus removal, the order of sensitivity to ultraviolet radiation resistance is denitrifying flora > PAOs > nitrobacteria > NPAB [18,20,21].

To achieve better removing effect of UV on COD, the lamp is 15 W, the time is 3 or 5 min; on TN, the time is 3 or 5 min; and on TP, the lamp is 10 W or 15 W, and the distance is 5 cm. Therefore, the better working condition of the four pollutants is 15 W, 5 min and 5 cm. It is recommended that the sewage treatment plant be equipped with an ultraviolet radiation device prior to the process, which can reduce the concentration of pollutants in the influent and make the subsequent process more effective in treating sewage. The ultraviolet radiation device is provided with a 15-W UV lamp 5 cm away from the surface and a stay of 5 min. This UV radiation device can be used as a pre-process for sewage treatment in a plateau environment.

5. Conclusions

The optimal removal rate of COD by UV radiation is 30.82%, and the corresponding working condition is the UV lamp of 15 W, the irradiation time of 0.5 min and the irradiation distance of 10 cm. The optimal removal rate of

TN is 48.52%, and the corresponding working condition is 18 W, 1 min and 20 cm. The best removal rate for NH_4^+–N is 17.36%, and the corresponding working condition is 20 W, 5 min and 20 cm. The best removal rate for TP is 30.98%, the corresponding working condition is 15 W, 3 min and 5 cm.

The order of UV radiation removal of four pollutants is TN > TP > COD > NH_4^+–N, and the order of sensitivity to UV radiation resistance is denitrifying flora > PAOs > nitrobacteria > NPAB. The better working conditions for the removal of the four pollutants are the UV lamp of 15 W, the irradiation time of 5 min and the irradiation distance of 5 cm.

Acknowledgments

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