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Performance evaluation of ultraviolet radiation and ozone disinfection for municipal secondary effluent reuse (Case study in Isfahan North wastewater treatment plant)

Mohammad Jamalinezhad[a], Amir Hessam Hassani[a,*], Mehdi Borghei[b], Mohammad Mehdi Amin[c]

[a]*Department of Environmental Engineering, Faculty of Natural Science and Environment, Science and Research Branch, Islamic Azad University, Poonak sq. Ashrafi Esfahani Blv., Hesarak, Tehran 14778-93855, Iran, Tel. +989121039899; email: ahhassani@srbiau.ac.ir (A.H. Hassani)*

[b]*Department of Chemical and Petroleum Engineering, Sharif University of Technology, Azadi Ave, Tehran 14588-89694, Iran, Tel. +989121130394; email: mborghei@sharif.edu*

[c]*Department of Environmental Health Engineering, School of Health, and Environment Research Center, Research Institute for Primordial Prevention of Non-communicable Diseases, Isfahan University of Medical Sciences, Hezar-Jarib Ave, Isfahan 81676-36954, Iran, Tel. +989133670508; email: amin@hlth.mui.ac.ir*

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ABSTRACT

This study aimed to evaluate and compare the performance of wastewater disinfection systems using ultraviolet radiation (UV) and ozonation to improve the secondary effluent quality of Isfahan North wastewater treatment plant. Therefore, the filtered effluent by a pretreatment unit from microscreen drum filter type with a pore size of 20 μm entered the disinfection pilots containing medium pressure (MP) UV lamps and ozonation system as tertiary treatment. In this study, the irradiation dose of UV (430–3,680 mW/cm^2), and injection dose (10–40 mg/L), and contact time (1–15 min) of ozonation were altered. The results showed that the total suspended solids were reduced by 61.27% at the maximum dose of UV radiation and 89.36% at the highest concentration and contact time with ozone. Though the turbidity and chemical oxygen demand were not reduced by UV, their maximum removal by ozone was 80.52% and 40.74%, respectively. The fecal and total coliform reduction at the maximum UV radiation was 3.82 and 3.79 log and at the highest concentration and contact time with ozone was 4.11 and 3.55 log, respectively. The results revealed that 300 W lamp with 40 s contact time and ozone dosage of 40 mg/L and the contact time of 15 min could meet the fecal coliform criteria recommended by the guidelines of the environmental protection agency for some uses, such as irrigation of restricted access areas and processed food crops or non-food crops.

Keywords: Ultraviolet radiation; Ozone; Disinfection; Reuse; Tertiary treatment; Microscreen

1. Introduction

The operating conditions of conventional treatment processes create different qualitative conditions for the effluent of biological treatment units, which sometimes do not meet the minimum quality standards because the treated wastewater contains a high percentage of pathogenic microorganisms, therefore requires a tertiary treatment, such as the use of disinfection technologies [1]. Considering the possible reuse of treated effluents, the selection of an appropriate disinfection method is of paramount importance.

* Corresponding author.

Disinfection methods with different action mechanisms used in wastewater disinfection have several advantages and disadvantages. The natural disinfection processes could represent valuable solutions due in particular to the absence of chemical reagents. Moreover, the advanced technologies are very interesting but they are still in the research state and restrict the use of these technologies on an industrial scale [2]. Ultraviolet radiation (UV) radiation and ozonation are among disinfection processes that are sensitive to influent qualitative parameters and have an effective performance in the case of creating appropriate quality conditions for influent wastewater [3].

UV transmittance and suspended solids content are the most important wastewater quality parameters affecting the UV disinfection efficiency [4]. UV irradiation with proper radiation dose is an effective disinfectant for bacteria, protozoa, and viruses in reclaimed water, while not contributing to the formation of toxic byproducts. Ozone is also a reactive oxidant and an effective viricide that does not produce dissolved solids and its effectiveness is not affected by the ammonium ion or the influent pH during disinfection [3]. Additionally, ozone is capable of reducing the UV absorbance and some pollutants such as odor, dye, and organic matter [5,6]. However, the amount of the required radiation in UV and the ozone required by ozonation depend on the influent qualitative parameters [7]. The presence of suspended solids affects the UV irradiation penetration. Moreover, the suspended solids and organic compounds influence the required ozone dose. Thus, it is necessary to use a pretreatment process prior to disinfection. This process can modify the physicochemical parameters to create the proper conditions for disinfection [8,9]. Microscreens are among pretreatment methods used for particle separation in tertiary treatment of biologically treated wastewater [10]. In this study, a microscreen drum filter was used as a pretreatment for UV and ozone disinfection.

The low-pressure (LP) UV lamps have been widely used in water and wastewater disinfection, however, the medium pressure (MP) lamps are more compact, powerful, and emit over a wider range of light than the more traditional LP lamps [11]. In this study, due to the effluent quality, the performance of MP lamps (150 and 300 W) in disinfection and tertiary treatment of Isfahan North wastewater treatment plant (INWWTP) as a pilot was investigated. In addition, given the ozone's ability to reduce some physicochemical parameters, the disinfection and tertiary treatment with ozone were also examined on a pilot scale to determine the specifications of each technique to achieve specific levels of effluent quality, and the performance of both methods in improving the secondary effluent quality was compared.

2. Materials and methods

In this study, the following pilot plants were installed in parallel at the outlet of the secondary sedimentation unit in INWWTP to investigate the performance of UV and ozone in tertiary municipal treatment: (1) 150 W MP lamp reactor, (2) 300 W MP lamp reactor, and (3) ozonation system. The pretreatment prior to disinfection systems was a microscreen drum filter with a mesh size of 20 μm. INWWTP consists of two phases, an old phase and a development phase that treat wastewater using an activated sludge process. The average treatment rate of INWWTP is 2 m^3/s.

2.1. UV disinfection

The UV lamps (150 and 300 W MP) were manufactured by France ARDA Company and the reactors were made of steel for each lamp. The schematic of UV pilot for each lamp is shown in Fig. 1. Table 1 shows the specifications of both lamps.

UV reactors were investigated in parallel with each other. Hydraulic residence time (HRT) was regarded as the irradiation time or exposure time, at four levels of 10, 20, 30, and 40 s. The inlet flowrate to each reactor was adjusted to be 2.2–8.8 L/min and 3.6–14.4 L/min to create four levels of exposure time for the 150 and 300 W lamp, respectively. The UV dose (D) for each lamp was calculated by multiplying the average UV intensity (I_{av}) by the exposure time (t) in unit of mW s/cm²:

$$D = I_{av} t \quad (1)$$

The average UV intensity was a function of the initial UV intensity of the lamp (I_0), irradiated sample depth (d), and the amount of radiation absorbed by the sample (α), and was calculated according to Eq. (2) [12]:

$$I_{av}\left(m / c^2\right) = I_0\left(\frac{1-1-\alpha}{\alpha_d}\right) \quad (2)$$

In this study, UV intensity was measured with a manually operated radiometer (IX EC Hanger) and about 5 min after startup, the constant lamp output (I_0) of 150 and 300 W lamps was 37 and 80 mW/cm², respectively. UV transmittance

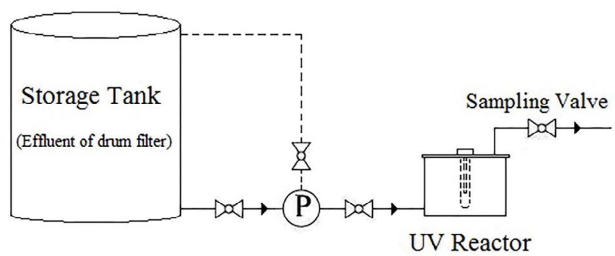

Fig. 1. Schematic of UV pilot.

Table 1
Characteristics of UV lamps

Model	UVOX150	UVOX300
Total length (mm)	66	101
Effective length (mm)	36	56
Diameter (mm)	12	10
Quartz height (mm)	110	110
Quartz diameter (mm)	30	40
Useful life (h)	10,000	10,000

was measured by a spectrophotometer (DR-5000, Model 8452A, Hatch-Lange) at the UV-C wavelength (254 nm) using a standard 1 cm quartz cuvette. According to Eq. (2), the UV dosage was set at four levels of 415; 830; 1,245; and 1,660 mW s/cm^2 for the 150 W lamp and at four levels of 920; 1,840; 2,760; and 3,680 mW s/cm^2 for the 300 W lamp. For each of UV dose levels, sampling was performed at 10, 20, 30, and 40 s from the output of each reactor.

2.2. Ozone disinfection

Ozone was produced with an ozone generator (Ozoneab Co., Iran) by the corona discharge method and was injected through a venturi ejector. Due to the supply of ozone contact time, the wastewater was circulated in a closed path post ozone injection. The specifications of the ozone pilot are presented in Table 2. Moreover, Fig. 2 displays the schematic of the ozone pilot plant.

In this study, the ozone dose and the contact time with ozone changed. The ozone injection dose was considered at four levels of 10, 20, 30, and 40 mg/L, and the ozone contact time was examined at four levels of 1, 5, 10, and 15 min. In order to provide ozone dose levels, a certain amount of ozone was injected to a certain volume of the filtered secondary effluent over a period of time-based on the ozone generator capacity. The ozonated feed then entered the reaction tower and was flowed in a closed circulation path for the sampling time of 1, 5, 10, and 15 min to properly mix ozone.

Table 2
Characteristics of ozone pilot

Oxygenating capacity (L/min)	66
Ozone generator capacity (g/h)	36
Contactor diameter (cm)	12.7
Contactor height (cm)	130
Injector size (in)	0.75

2.3. Sampling

For each UV lamp, sampling was done twice at all four levels of irradiation dose, before, and after the reactor. Additionally, based on the factorial statistical method, at all four levels of ozone dose and all four levels of ozone contact time, 16 sampling steps were carried out with twice repetition. According to the similar influent quality, 20 samples for UV reactors and 40 samples for ozone pilot were collected at all exposure time levels of each UV dose and all contact time levels of each ozone dose.

In this study, physicochemical water-quality parameters, including total suspended solids (TSS), turbidity, chemical oxygen demand (COD), and pH were measured according to the Standard Methods [13]. Microbiological experiments were carried out using 15 tubes most probable number method (MPN) and in different dilutions depending on the quality of each sample, irradiation dose, and ozone dose. For bacteriological analysis, the effluent samples were collected in sterile glass bottles (250 mL) and analyzed immediately after collection. The collected data was analyzed using statistical methods of analysis of variance (ANOVA) and paired *t*-test.

3. Results and discussion

Experiments were performed on the filtered secondary effluent fed to three different pilot plant disinfection alternatives. Table 3 summarizes the range of the INWWTP filtered secondary effluent characteristics. The samples pH was measured to be between 6.7 and 8.8.

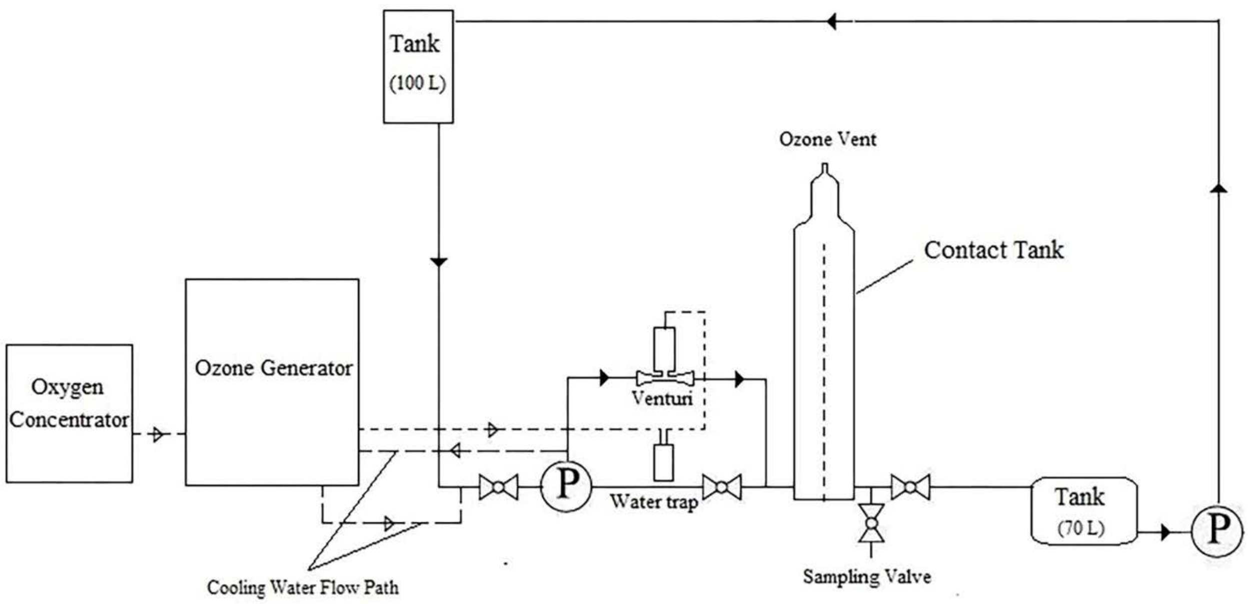

Fig. 2. Schematic of ozone pilot plant.

Table 3
Filtered secondary effluent characteristics of INWWTP

TSS (mg/L)	14–44
Turbidity (NTU)	5.1–16.8
COD (mg/L)	24–97
Fecal coliform (MPN/100 mL)	1.7×10^5–1.6×10^6
Total coliform (MPN/100 mL)	3.5×10^5–9.2×10^6

3.1. Total suspended solids

There was a significant difference between TSS concentrations before and after irradiation of filtered effluent with MP UV lamps ($P < 0.05$), indicating that unlike LP lamps, the radiation intensity at the UV dose of 400–3,700 mW s/cm^2 was able to reduce the suspended particles and to some extent affected the structure of some suspended solids and broke them down. At the lowest and highest levels of UV dose, the minimum and maximum removal of TSS for the 150 and 300 W lamps were 11.43% and 58.77%, and 12.68% and 61.27%, respectively. The TSS removal percentages for different doses of MP lamps are shown in Fig. 3.

As shown in Fig. 3, the percentage of TSS removal rises linearly for each lamp as the UV dose increases. Based on the statistical analysis of a one-way ANOVA test, a significant difference was observed between the percentages of TSS removal at different levels of UV dose for each lamp. Moreover, at the same UV dose per lamp (920.72–1,663.88 mW s/cm^2), the percentage of TSS removal in the 150 W lamp was higher than the 300 W lamp, indicating the effect of more exposure time at similar UV doses. In other words, the exposure time parameter had a greater effect on TSS removal than the UV intensity parameter. As shown in Fig. 3, the TSS removals at different levels of UV dose per lamp are close to each other, and the performance of both lamps is almost the same with regard to the suspended solids.

The results of two-way ANOVA showed that the difference between the percentages of TSS removal at ozone dose levels and contact time levels with ozone was significant and there was no interaction between them. Accordingly, there was a significant difference between the fourth level of ozone dose and the third and fourth levels of ozone contact time compared to other levels, indicating the effect of high ozone dose and longer contact time on suspended solids reduction. The values of TSS removal vs. ozone contact time are shown for each ozone dose level in Fig. 4. Fig. 4 demonstrates that the TSS removal efficiency has increased linearly by increasing contact time for each ozone dose level. In addition, by increasing the ozone dose, the TSS removal percentage has increased. The relatively equal distance of parallel lines in Fig. 4 indicates the lack of interaction among the studied variables.

The minimum and maximum removal of TSS for ozone concentration of 10 and 40 mg/L and the contact time of 1 and 15 min was 14.29% and 89.36%, respectively. Liberti et al. [14] also showed that the oxidation of organic suspended solids by ozone and the production of soluble organic compounds would reduce the TSS parameter. In similar research by Martínez et al. [15], the percentage of suspended solids (SS) removal with the input concentration of less than about 20 mg/L and ozone dose of 11–13 mg/L was reduced on average by 30% and up to 75%. Therefore, the UV performance with MP lamps for TSS removal was competitive with the first and second levels of ozone injection dose in ozone pilot plant, and by increasing ozone dose levels, ozonation showed better performance than MP UV lamps.

3.2. Turbidity

Similar to the results of studies on LP lamps, MP lamps were not able to significantly reduce turbidity and a small percentage of its removal by MP lamps can be interpreted as reducing TSS and turbidity associated with suspended solids. However, the results of two-way ANOVA showed a significant difference between the percentages of turbidity removal at ozone dose levels and contact time levels. The results also showed no interaction between them.

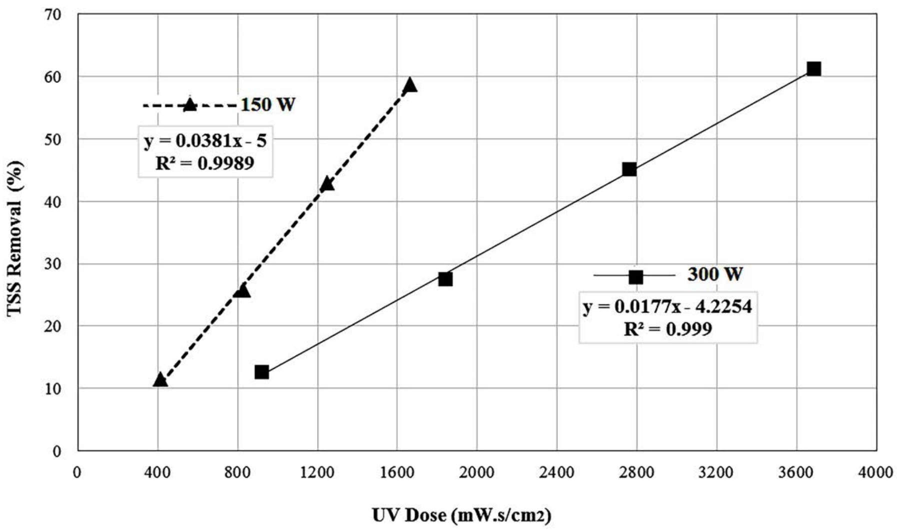

Fig. 3. TSS removal efficiency vs. UV dose.

The values of turbidity removal vs. ozone contact time are presented for each ozone dose in Fig. 5. As shown in Fig. 4, by increasing contact time for each ozone dose level, the efficiency of turbidity removal increased and it was quite linear for ozone dose of 10 and 40 mg/L. According to statistical results, there was a significant difference between the first level of ozone contact time and other levels.

Failure to increase the turbidity removal percentage in proportion to the increased ozone dose can be attributed to the higher influent turbidity at dosage levels of 10 and 40 mg/L (11.42 and 12.14 NTU) rather than at 20 and 30 mg/L (5.69 and 6.86 NTU), different particle sizes distribution within the ozone pilot, and different effects of ozone on them. Accordingly, because of the low concentration of influent turbidity and the amount of injected ozone, there was a significant difference between the second level of ozone dose with the first and third levels. Additionally, the relatively equal distance of parallel lines in Fig. 5 indicates the lack of interaction among the studied variables.

The rate of turbidity removal was 18.12%–80.52% based on the influent turbidity. Martínez et al. [15] showed that ozone noticeably reduced turbidity, particularly when the input turbidity levels were higher. In addition, in a study conducted by Petala et al. [16], ozone injection through a diffuser at a concentration of 26.7 mg/L resulted in the removal of turbidity up to 80% and a concentration of 1.2 NTU.

3.3. Chemical oxygen demand

Similar to the results of studies on LP lamps, MP lamps were not able to significantly reduce COD and a small percentage of COD removal by MP lamps can be interpreted

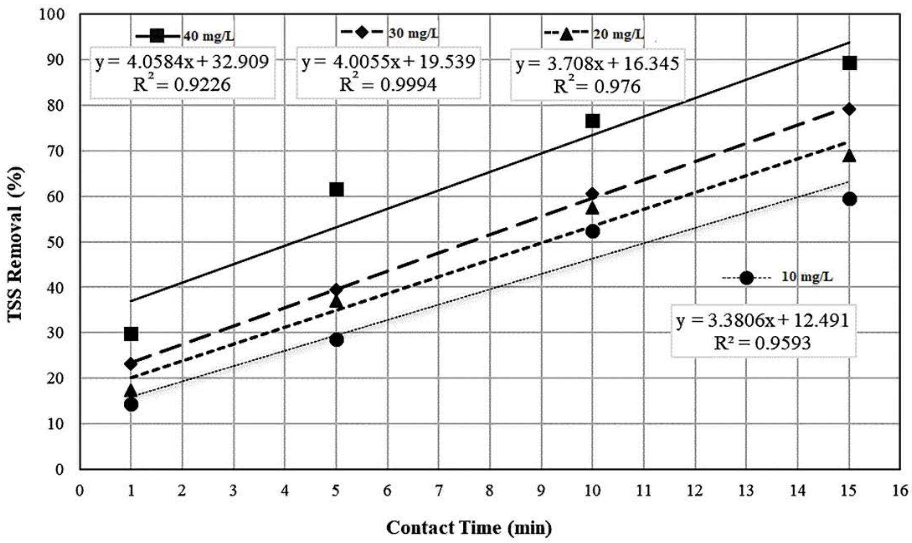

Fig. 4. TSS removal efficiency vs. ozone contact time for each ozone dose level.

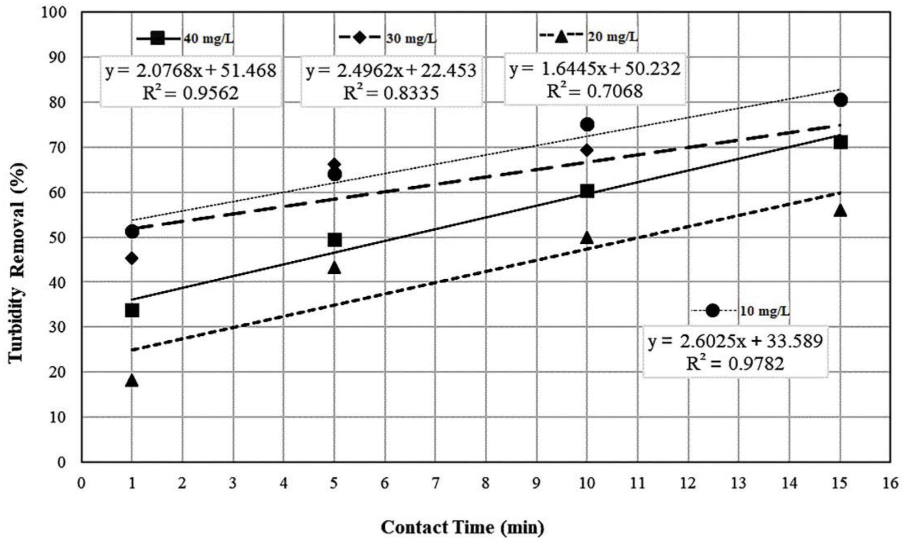

Fig. 5. Turbidity removal efficiency vs. ozone contact time for each ozone dose level.

as the reduction of COD associated with suspended solids. However, the results of two-way ANOVA showed that the difference between the COD removal percentage at ozone dose levels and the contact time levels was significant and there was no interaction between them. The values of COD removal vs. ozone contact time are shown for each ozone dose in Fig. 6. According to Fig. 6, by increasing contact time at other ozone dose levels, the percentage of COD removal increased linearly. The statistical results showed that the difference between the first level of contact time with ozone and the fourth level was significant.

Failure to increase COD removal percentage in proportion to an increase in ozone dose indicates that the ozone oxidation rate and COD reduction are directly related to the influent COD concentration. For high COD concentrations at the fourth level of ozone dose (94 mg/L), ozone had a lower tendency to reduce the organic matter than other levels and for low COD concentrations at the first and third levels of ozone dose (27 and 37.5 mg/L) had a higher tendency. Accordingly, despite the high ozone concentration at the fourth level of ozone dose, there was a significant difference between the fourth level of ozone dose and the first and third levels.

Lazarova et al. [9] also showed that the wastewater quality and, in particular, suspended solids and organic content strongly influence the required ozone dose for a given level of disinfection and the concentration of the transferred ozone and disinfection efficiency varied as the quality decreased (the increased TSS and COD). Furthermore, using a pilot with diffuser injection, Absi et al. [17] showed that low COD concentrations lead to a higher ozone residual and lower ozone consumption rates.

In this study, the removal rate of COD was 1.6%–40.74% based on the influent COD. In similar studies, the ozone dosage of 14 mg/L reduced the COD parameter by approximately 5% at an average concentration of 99 mg/L [17] and the highest percentage of COD reduction (with an initial concentration of 155 mg/L) at an ozone dose of 20 mg/min, obtained 36% [18]. Moreover, Martínez et al. [15] obtained an average of 30% COD removal at an influent concentration of less than about 20 mg/L and at an ozone concentration of 11–13 mg/L.

3.4. Fecal and total coliform

The difference between the concentrations of fecal and total coliforms, before and after irradiation of the filtered effluent by MP UV lamps was significant ($P < 0.05$); indicating that the UV radiation was effective in reducing microbial load. In Figs. 7 and 8, the percentage of fecal and total coliform removal has been presented as a function of the UV dose.

Fig. 7 shows that by increasing the UV dose, the percentage of fecal coliforms removal increased as a quadratic function for the 150 W lamp and as a cubic function for the 300 W lamp. In Fig. 8, the total coliform was increased as a linear function for a 150 W lamp and as a cubic function for the 300 W lamp. Additionally, in the 300 W lamp, the percentage of the fecal and total coliform removal by about 2,700 mW s/cm^2 UV dose (exposure time of about 30 s) showed an upward trend with a negative slope, and then, there were no noticeable changes. In other words, in a 300 W lamp, a contact time of at least 30 s is enough to remove coliforms. Similar to TSS conditions, at the same UV dose per lamp (920.72–1,663.88 mW s/cm^2), the percentage of fecal and total coliform removal in the 150 W lamp was approximately equal to or higher than the 300 W lamp, which indicates the effect of more exposure time in similar doses of UV. Thus, the exposure time had a greater effect on coliform removal than the UV intensity. The results showed that at the first instants of exposure to UV irradiation of 37 and 80 mW/cm^2 (in the first 10 s), a major inactivation occurred. In a similar study by Mounaouer and Abdennaceur [19], the UV kinetic studies revealed that the first instants of exposure (2–10 s) to a UV intensity of 5–8 mW/cm^2 is a deciding factor in UV disinfection.

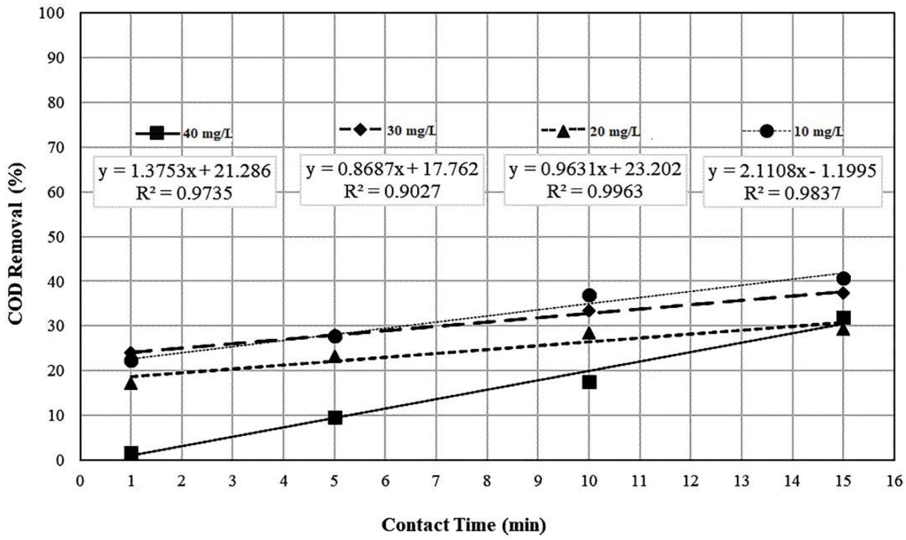

Fig. 6. COD removal efficiency vs. ozone contact time for each ozone dose level.

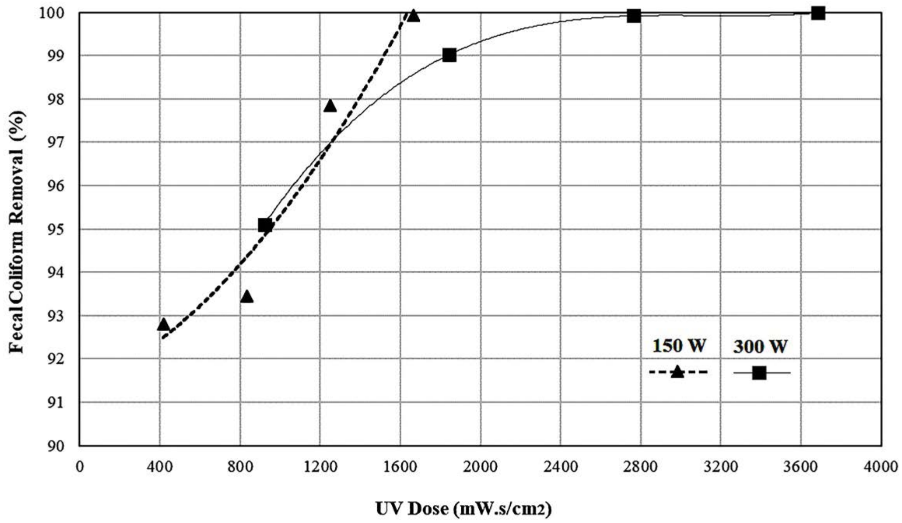

Fig. 7. Fecal coliform removal efficiency vs. UV dose.

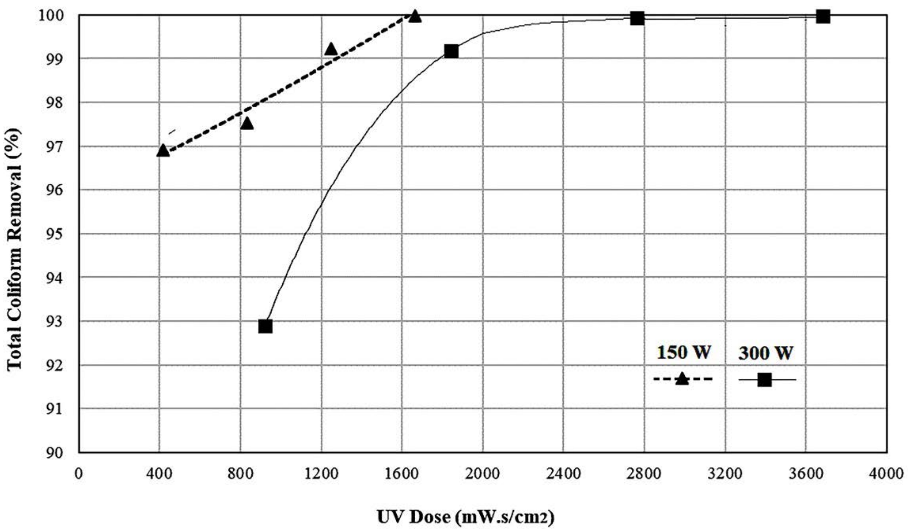

Fig. 8. Total coliform removal efficiency vs. UV dose.

The fecal and total coliform respectively reduced by 92.792%–99.929% (1.14–3.15 log) and 96.904%–99.976% (1.51–3.62 log) in the presence of the 150 W lamp at the UV dosage of 415–1,660 mW s/cm^2. Additionally, in the presence of the 300 W lamp at the UV dosage of 920–3,680 mW/cm^2, the fecal and total coliform reduced by 95.103–99.985 (1.31–3.82 log) and 92.883%–99.984% (1.15–3.79 log), respectively. Fecal coliform reduced to 550 MPN/100 mL in the 150 W lamp with an exposure time of 40 s and to 615 and 110 MPN/100 mL in the 300 W lamp with an exposure time of 30 and 40 s, respectively. Kamani et al. [20] also showed that in the disinfection of milk industry wastewater by the 300 W MP lamp and the contact time of 10 and 30 s, the total coliform is less than 1,000 MPN/100 mL and 270 MPN/100 mL, respectively.

Based on the one-way ANOVA statistical analysis, a significant difference was observed for the percentage of fecal and total coliform removal at different levels of UV dose for each lamp. There was a significant difference for fecal coliform in the 150 W lamp between the first and fourth levels and for fecal and total coliform in the 300 W lamp between the first level and other levels, indicating the high efficiency of coliforms elimination at high levels of irradiation and exposure time. However, despite the major reduction of coliform values at the early times, it is necessary to investigate the higher levels of the UV dose and exposure time in order to reduce the coliforms to less than the specified levels in different standards.

The results of two-way ANOVA showed that the difference between the percentage of fecal and total coliform removal at ozone dose levels and contact time levels and the interaction between them was also significant. Accordingly, there was a significant difference between the first and second levels of ozone dose and the third and fourth levels.

Moreover, there was a significant difference between the first level of ozone contact time and other levels, indicating the effect of high ozone dose and longer contact time on coliforms reduction. The values of fecal and total coliform removal vs. ozone contact time are shown for each ozone dose level in Figs. 9 and 10. As shown in Figs. 9 and 10, by increasing the ozone contact time at each ozone dose level, the percentage of fecal and total coliform removal increased logarithmically. In addition, the major reduction of coliforms, especially at the second to fourth ozone dose levels (20–40 mg/L) occurred in the first minute.

The increased coliform removal rate caused by the increase of ozone dose in Figs. 9 and 10 showed that the difference in influent turbidity and COD at the second and fourth levels of ozone dose (5.69 NTU and 42.5 mg/L and 12.14 NTU and 94 mg/L, respectively) could not disturb the disinfection rate according to ozone dose level. In other words, because of the fast kinetics between ozone and coliform bacteria, in the conditions investigated in this study, the inactivation is less affected by influent wastewater quality (COD and turbidity).

Lazarova et al. [9] also showed that the fecal coliform inactivation did not change during the hydraulic retention time of 2 and 10 min and due to the quick decay of ozone post-injection, and no further inactivation was observed. In Liberti et al.'s [14] research, the inactivation also occurred by ejector injection with a very sharp initial slope at 0.1 min and almost completed after 5 min and Xu et al. [21] showed that the hydraulic retention time of 2 min was sufficient for efficient fecal coliform inactivation.

The minimum of fecal and total coliform removal with ozone dose of 10 mg/L and 1 min contact time was 46.575%

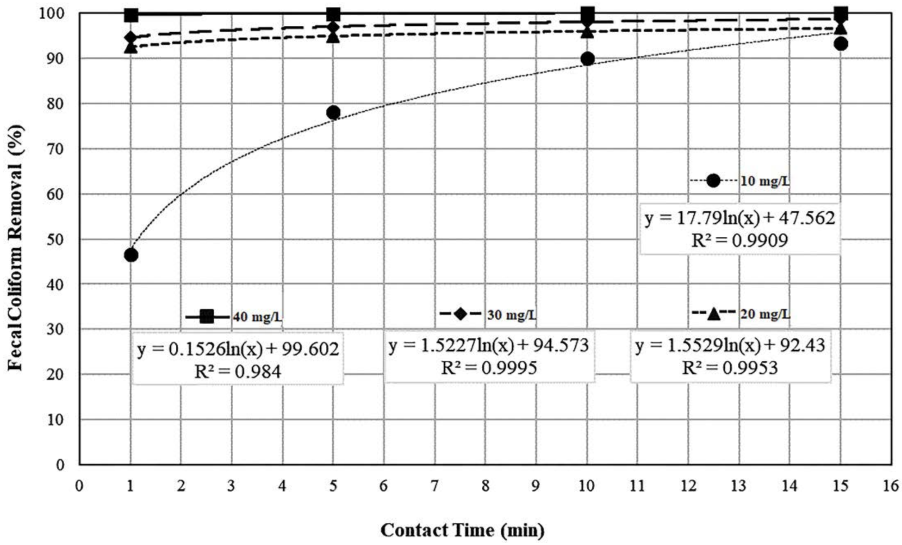

Fig. 9. Fecal coliform removal efficiency vs. ozone contact time for each ozone dose level.

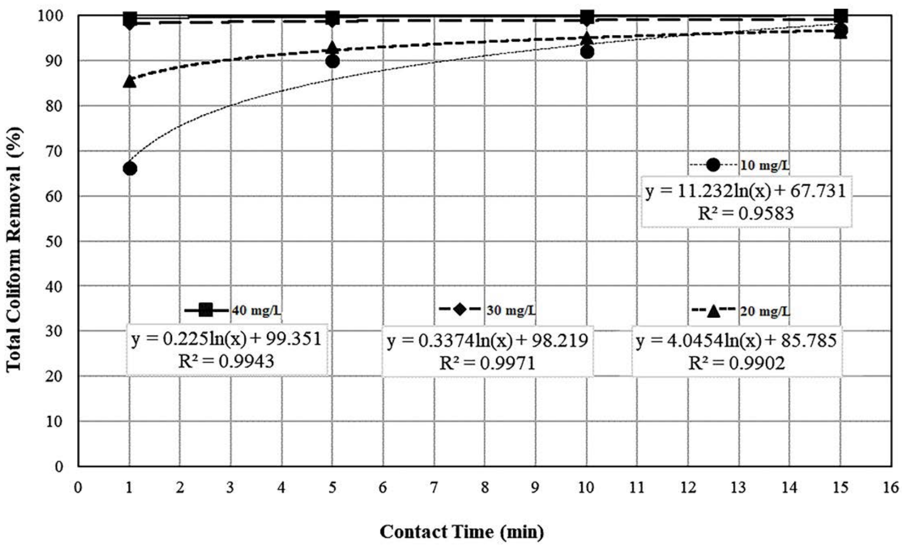

Fig. 10. Total coliform removal efficiency vs. ozone contact time for each ozone dose level.

and 66.250% (0.27 and 0.47 log), respectively and the maximum of them with ozone dose of 40 mg/L and the contact time of 15 min was 99.992% and 99.972% (4.11 and 3.55 log), respectively. In a similar study conducted by Gehr et al. [7] on a laboratory reactor, the transferred ozone dose to reduce approximately 2-log fecal coliform for low-quality wastewater was obtained to be 30–50 mg/L. Also, Nasuhoglu et al. [22] concluded that the required ozone dose to satisfy 200 MPN/100 mL total coliform (>4-log reduction) for high suspended solids, organic and microbial load was more than 40 mg/L.

4. Conclusions

Based on the results of this site-specific study, we concluded that the UV irradiation with MP lamps at moderate to high doses (400–3,700 mW s/cm^2) is suitable for reducing the bacteria and TSS load, and ozonation at high concentration (10–40 mg/L) is effective for reducing the investigated physical and chemical parameters in this study.

The performance of MP UV lamps (150 and 300 W) for suspended matters removal was almost the same and competitive with the first and second levels of ozone dose (10 and 20 mg/L). In addition, the radiation exposure time has a greater effect on the TSS and coliform removal than the UV dosage.

In ozonation, the quality of the filtered secondary effluent (turbidity and COD) has a greater effect on the percentage of turbidity and COD removal than the ozone injection dose, but within the range of the investigated qualitative parameters of this study, they could not disrupt the disinfection rate according to ozone dose levels.

The 300 W MP lamp with an exposure time of 40s (3,700 mW s/cm^2) and ozone with a 40 mg/L injection dose and a contact time of 15 min can reduce the fecal coliform according to the Environmental Protection Agency's (EPA) recommended instructions for some uses, including irrigation of the restricted access areas and processed food crops or non-food crops (fecal coliform ≤ 200 MPN/100 mL). The pilot-plant experiments suggest that the planned tertiary treatments (microscreen drum filter + MP UV lamps/ozonation) could readily be converted into a full-scale installation at the investigated WWTP.

Acknowledgments

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