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Pilot-scale studies of combined clarification, filtration, and ultraviolet radiation systems for disinfection of secondary municipal wastewater effluent

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ABSTRACT

Disinfection of municipal wastewater effluent was evaluated using three alternatives, including: (1) low-pressure (LP) + medium-pressure (MP) UV lamps; (2) clarifier + LP + MP; and (3) pressurized sand filter + LP + MP. Total coliform (TC), fecal coliform (FC), fecal Streptococcus (FS), TSS, several physicochemical parameters, absorbtivity and UV transmittance (UVT; %) were tested. The UVT% for secondary, clarified and filtered effluents were 3.5, 34 and 50, respectively. A 15% photo-reactivation in secondary effluent disinfected by LP lamp was observed, while it was limited to 0.03% by the MP lamp after filtration. Filtration to a surface overflow rate (SOR) of 1050 $L/m^2 h$, followed by MP irradiation at a dose of 230 mW s/cm^2 was an effective alternative to reduce the TC, FC, and FS in the disinfected secondary effluent. Filtration + MP lamp met the standards of 1000 TC and 400 FC/100 mL for effluent discharge to receiving waters. This process can also inactivate FS, effecting a 6-log reduction. Among the evaluated alternatives, none of the other treatment systems performed as well as the pressurized sand filter + MP lamp, making this the best combination for post-treatment and disinfection of secondary effluent from a well-run wastewater treatment plant.

1. Introduction

Inadequate water supplies and increasing pollution in many parts of the world have become a growing concern during the past quarter-century [1]. Reclamation and reuse of municipal wastewater has increased in recent years. However, reuse must be safely implemented to avoid endangering public health and the environment [2]. The elimination of microbes in treated wastewater is often necessary [3]. In a very limited number of cases, treated wastewater discharges without disinfection are permitted; these are approved on a case-by-case basis [4]. The development of new technologies has extended the possibilities for wastewater reuse [5].

An increasing awareness of the disadvantages of chemical disinfectants has resulted in the selection of UV radiation as a promising alternative. In 1998, nearly 300 operating wastewater treatment plants were using UV disinfection [6]. More than 2000 installations using UV radiation have been implemented to disinfect primary, secondary and tertiary effluents [3]. The number of utilities using UV disinfection has increased considerably and is expected to increase significantly over the next decade [6]. UV disinfection systems are an effective, low-cost, and environmentally friendly way to disinfect wastewater for reuse [5]. One of the factors affecting the performance of UV disinfection is the quality of the wastewater [6]. UV efficiency is primarily limited by suspended solids (SS), thus UV light is most efficiently used for the disinfection of advanced-treatment effluent because of its reduced suspended solids concentration [4]. Disperse coliform bacteria are readily inactivated because they are fully exposed to the average UV light intensity as compared to particle-embedded microorganisms. Hence, particulate matter must be removed from effluent prior to disinfection with UV [7]. High SS, turbidity and iron, as well as low UV transmittance will compromise UV performance [8]. The required UV dosage for any specific treatment plant will vary depending upon the treatment process, quality of water being disinfected and the targeted micro-organisms [7]. Further research is needed to estimate the applicable range of UV disinfection in different locations and environments [9]. The most suitable pretreatment technologies for SS reduction are physical treatments including clarification and filtration.

It is strongly recommended that a filtration system be installed prior to a UV disinfection system. A filter can lower turbidity and consequently itself remove a fraction of the pathogens. As a result, UV disinfection loading can be reduced [3]. The best way to ensure that the filter configuration selected for a given application will function

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properly and the effluent water quality is maintained within prescribed limits is to conduct pilot-scale studies [7]. Due to the variable nature of wastewater composition between communities, the required UV doses and lamp types must be determined on a site-specific basis [10]. Furthermore, because the characteristics of the effluent suspended solids also vary with the organic loading on the process as well as with the time of day, filters must be designed to function under a rather wide range of operating conditions [7]. Many studies around the world have evaluated UV disinfection performance. In a filtration + UV radiation system, a dose of 16 J/m^2 was required to reduce fecal coliform counts in the final effluent to lower than 10 FC/100 mL [11]. Comparing lamp types in the disinfection of filtered effluent with UVT = 65, the UV operating doses required to achieve a 2.7–2.9 log reduction were 26, 30 and 32 mW s/cm^2, respectively, for the low-pressure, low-intensity (LP–LI), low-pressure, high-intensity (LP–HI) and medium-pressure, high-intensity (MP–HI) systems [10]. For secondary effluent samples, the required UV dose to achieve effluent fecal concentrations of less than 2000 FC/100 mL varied from 30 to 60 mW s/cm^2. For tertiary effluent the required UV dose to meet the 10 FC/100 mL was 40–50 mW s/cm^2 [12]. There are no general regulations or effluent limitations for UV dosing in treated wastewater disinfection. However, a dosage of 50–400 mJ/cm^2 is often adopted in practice [3]. In the present study, three alternatives for secondary effluent disinfection were evaluated, with and without pretreatment units in pilot scale. Clarification, pressurized sand filtration and UV disinfection were the operations and process units combined in the different alternatives in this study.

2. Materials and methods

2.1. Pilot plants

To study the effects of site-specific parameters on a UV disinfection system, three pilot plants with different alternatives including: (1) secondary effluent + low pressure (LP) + medium pressure (MP); (2) clarification + LP + MP; and (3) filtration + LP + MP, were designed and installed in parallel at the Isfahan North wastewater treatment plant (WWTP). Pretreatment prior to UV radiation disinfection consisted of clarification (a 2 m^3 volume with a detention time of 1 day) and filtration by sand pressure filter (1 m media depth with 0.4 and 0.6 mm effective particle size for the sand, SOR = 84 to 1091 L/m^2 h). UV radiation was applied in tubular modules with low-pressure (55 W, monochromatic) and medium-pressure (300 W, polychromatic) UV lamps connected in series to the units in each line. The schematic design for the pilot plant is shown in Fig. 1. The pilot plant was operated under varied of conditions, including UV dose and effluent type (secondary, clarified and filtered effluents). The dose varied according to the initial intensity of the lamp, the flow rate and influent transmittance. The filter was characterized by a filtration surface of 1.43 m^2 and a height of 2 m, with a hydrostatic pressure tolerance of 5 bars, and was operated at 2 bars. As soon as the effluent total suspended solids (TSS) or head loss were increased, the sandy media was backwashed with air and clean water. To evaluate the filter performance, the filtration rate (SOR) was controlled by metering the influent flow rate.

Concerning the UV disinfection, doses ranging from 100 to 1000 mW s/cm^2 were considered for a maximal flow rate of 26 L/min. The average treatment rating of Isfahan North WWTP is 1.5 m^3/s. The facility consists of two phases, an old phase and a development phase, treating wastewater using an activated sludge process. A pilot plant was constructed at the site of the treatment plant and secondary effluent at a flow rate of 1 m^3/h was pumped from the mixed discharge zone of the two phases to the pilot. The pilot plant included pretreatment units and two UV disinfection reactors containing either LP–HI or MP–HI lamps, and also both of them in series.

The UV dose for the both low- and medium-pressure systems was controlled by adjusting the flow rate. The data collection program focused on evaluating the effectiveness of UV disinfection through microbial analysis and photo-reactivation testing, as well as the water quality and operational impacts on UV disinfection.

2.2. Calculation of irradiation dose

The theoretical hydraulic residence time (HRT) was deemed a reasonable estimate of the actual residence time [10]. Therefore, UV dose (D) were calculated in units of mW·s/cm^2 [dose = (flow × UV intensity) ÷ reactor volume] (Eq. (1)).

$$D = I_{avg} \times t \tag{1}$$

Based on radiometer readings of intensity (I_0), absorptivity (α) and irradiated sample depth (d); the average intensity, I_{avg} (in mW/cm^2) was calculated as Eq. (2) [13].

$$I_{avg}(\mathrm{mW/cm^2}) = I_0\left(\frac{1-10^{-\alpha.d}}{\alpha \times d}\right) \tag{2}$$

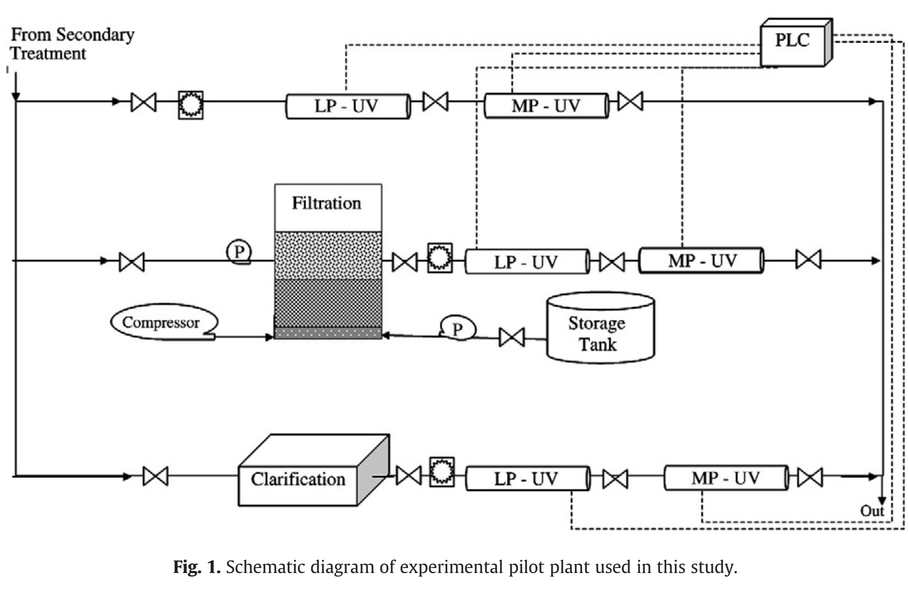

Fig. 1. Schematic diagram of experimental pilot plant used in this study.

In this study, UV intensity was monitored with a manually operated radiometer (IX EC Hanger) using probe C for the detection of germicidal UV wavelengths for the LP and MP lamps. The initial intensity (I_0) of the lamps was measured about 5 min after lamp start-up. These values were variable in the first period of pilot operation. Generally, the constant lamp outputs (I_0) of both lamps were 8 and 82 mW/cm^2 respectively. However, the initial intensity of the LP lamp was reduced due to on/off cycling to about 7 mW/cm^2 in the last period of pilot operation. The HRT was calculated as the volume irradiated by the lamps divided by the measured average flow ($t = {}^V/_Q$).

2.3. Sampling

Grab samples for chemical analysis and microbial enumeration were collected from the sampling ports upstream and downstream of the pilot units once a week; 17 effluent samples were collected over a 5-month period (January to May 2009). A total of 204 samples were taken from 12 sampling ports of the pilot plant in the three different alternatives, including before and after the sand filter, clarifier, single LP, single MP, and combined LP and MP. Total coliform, fecal coliform and fecal Streptococcus was analyzed as microbiological parameters in all effluent samples.

Physicochemical water-quality parameters measured in the system included TSS, 5 days biological oxygen demand (BOD_5), chemical oxygen demand (COD), volatile suspended solids (VSS), pH, hardness, total iron, absorptivity and UV-transmittance percentage (UVT, %). All the experiments were carried out according to the Standard Methods [14]. It was hypothesized that suspended solids may account for a significant portion of the unfiltered effluent UVT. Hence, UV transmittance was measured with a spectrophotometer (DR-5000, Model 8452A, Hatch-Lange) at the UV-C wavelength (254 nm) using a standard 1-centimeter quartz cuvette. For bacteriological analysis, effluent samples were collected in sterile glass bottles (250 mL) and analyzed immediately after collection.

2.4. Inactivation of bacteria

A Chick–Watson relation was used for computing the log-linear inactivation of disperse coliform bacteria in a UV Disinfection system, as given by Eq. (3):

$$N_t = N_0 \times e^{-k.d} \tag{3}$$

To evaluate the photo-reactivation ability of bacteria, the remaining volume of UV-exposed samples was exposed to sunlight with an intensity of 6000 lux for 3 h and the bacterial counts were determined. The percentage of photo-reactivation (P) was computed by Eq. (4) [15]:

$$P(\%) = \frac{\left(N_p - N_t\right)}{\left(N_0 - N_t\right)} \times 100 \tag{4}$$

The collected data were analyzed by the statistical methods of analysis of variance (ANOVA) and paired t-test.

3. Results

Experiments were performed on the secondary effluent fed to three different pilot-plant disinfection alternatives. Table 1 summarizes the mean values for the WWTP secondary effluent characteristics.

3.1. Performance of the pretreatment units

Figs. 2 and 3 demonstrate the efficiency of clarification and filtration in the reduction of the chemical and microbial parameters as a pretreatment process for UV disinfection systems. Fig. 4 shows the UVT% in different effluents.

3.2. Bacterial inactivation results

The logarithmic inactivation of target bacteria by LP, MP and a combination of both of the lamps are shown in Figs. 5–7. The expression of $-\log(N_p/N_0)$ is showing the logarithmic inactivation of bacteria. in other words, photo reactivated number ratio to primary number of bacteria.

3.3. Bacterial photo-reactivation results

The results of the photo-reactivation studies are shown in Figs. 8–10.

4. Discussion

As shown in Figs. 2 and 3, in the clarification tank, removal efficiencies of TSS, BOD_5, COD and VSS were 69, 41, 52 and 41%, respectively; removal efficiencies of TC, FC and SF in the clarification tank were 64, 67 and 66%, respectively. Concerning the reduction of chemical parameters, filtration was the technique with the higher performance. Mean values of TSS, BOD_5, COD, and VSS in effluent filtered at a flow rate of 25 L/min and an SOR of 1050 L/m^{2}h were 24,

Table 1
Secondary effluent characteristics fed to pilot plant.

pH	VSS (mg/L)	COD (mg/L)	BOD (mg/L)	TSS (mg/L)	TC MPN/100 mL	FC MPN/100 mL	FS MPN/100 mL
7.1	145	843	350	194	5.3×10^6	2.1×10^6	2×10^5
6.9	84	214	92	150	1.7×10^7	5.3×10^6	3.8×10^5
7.2	93	343	240	124	1.6×10^6	6.7×10^5	1.1×10^4
6.8	138	168	75	142	1.3×10^7	7.2×10^6	4×10^5
6.5	72	215	93	184	6.8×10^5	6×10^4	3.3×10^4
7.4	63	173	83	118	4.2×10^5	6.3×10^4	5.6×10^5
7.1	42	186	87	134	6.9×10^7	8.6×10^6	8.9×10^5
6.9	94	257	112	137	8.9×10^6	5.5×10^6	1.3×10^4
7.4	108	438	214	134	9.6×10^6	3.3×10^5	4.5×10^4
6.4	86	316	115	104	1.6×10^6	5.5×10^5	2.2×10^4
6.5	52	210	74	165	2.1×10^5	1.8×10^5	1.7×10^4
7.2	44	186	62	104	5.6×10^5	1.7×10^5	6×10^4
7.5	72	221	97	152	7.2×10^6	3.5×10^5	4×10^4
7.1	94	246	93	109	2.3×10^6	7.4×10^5	3.8×10^4
6.9	114	343	112	115	4.2×10^5	5.2×10^4	5.7×10^4
7.2	102	270	120	106	2.1×10^6	6.1×10^5	4×10^4
7.2	95	214	116	102	1.4×10^6	2.7×10^5	4×10^4

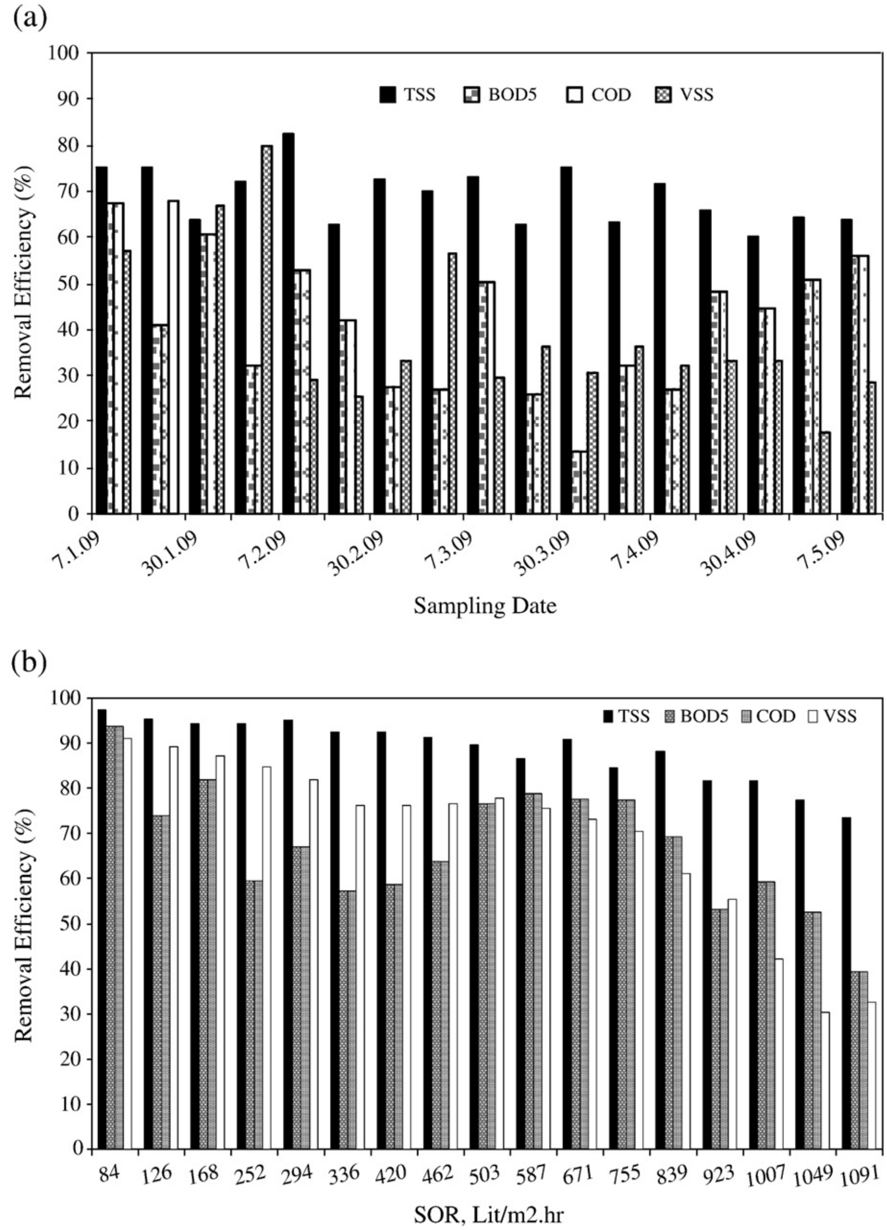

Fig. 2. Removal efficiency of: (a) clarification and (b) filtration for the reduction of physical and chemical parameters of the secondary effluent.

128, 146 and 71 mg/L, respectively. Therefore, the efficiency of the filter in TSS removal was 89%, and logarithmic reductions of TC, FC and FS were 0.24, 0.22 and 0.29, respectively.

Using granular media filtration, the highest previously reported removal rates in tertiary treatment are 70, 56, 38 and 54% for TSS, VSS, COD and BOD, respectively [16]. If the sand filter conditions are selected correctly, the physicochemical quality of water would be ameliorated, and consequently the disinfection performance would also be improved [17].

UV transmittance represents the percentage of UV energy in the water that reaches the microorganisms. This parameter is dependent on the spacing of the lamps and the water quality of the effluent. High suspended solids concentrations are associated with low UV transmittance. Mean UVT values in the secondary, clarified and filtered effluents were 3.5, 34 and 50%, respectively. In addition, the UV absorbances at 254 nm in the three kinds of effluent were measured at 1.6, 0.47 and 0.3 au/cm, respectively. As shown in Fig. 4, secondary and filtered effluent transmittances exhibited good correlations with suspended solids. However in the clarified effluent, because of the constant detention time in the clarification tank (1 day) and the consequent removal of mainly the large particles, the correlation of TSS and UVT was weak.

In fact, the clarification tank played the role of an equalization tank, moderating the secondary effluent fluctuations. Plots of the log reduction versus UV dose for the three alternative UV systems are shown in Figs. 5–7. Inactivation of bacteria within the secondary effluent was not feasible at the conventional doses. These microorganisms are effectively shielded from the damaging effects of UV light, so the light penetration was incomplete. In the secondary effluent (without pretreatment), many of the coliform organisms were either clumped or particle-associated, which requires increased UV dosage. Unfortunately, increasing the UV intensity by MP lamp or a combination of LP and MP lamps did not have a significant effect on reducing the number of surviving particle-associated coliform bacteria.

The absorption of UV radiation by particles in reclaimed water is typically 10,000 times or more great than by the bulk liquid medium.

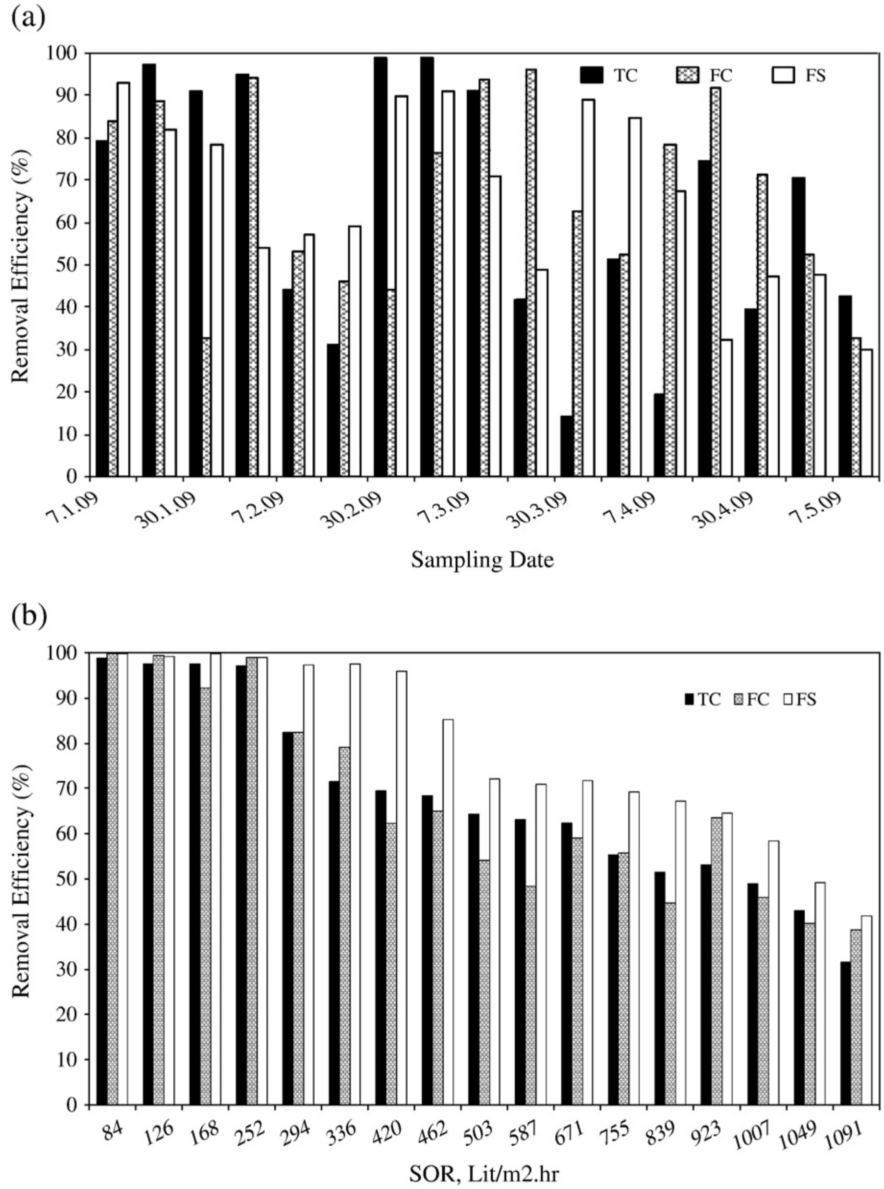

Fig. 3. Removal percentages of secondary effluent microbial parameters by (a) clarification and (b) filtration.

It was observed that in disinfection of the secondary, clarified and filtered effluents with the LP lamp, UV radiation doses of 161, 400 and 152 mW s/cm^2, respectively, were necessary to reduce the target bacteria to below the standard levels (1000 TC, and 400 FC/100 mL) and to inactivate the FS by 6-log. However, in disinfection of the secondary, clarified and filtered effluents with the MP lamp, doses of 516, 576 and 230 mW s/cm^2, respectively, were necessary to reduce the target bacteria value down to standard levels.

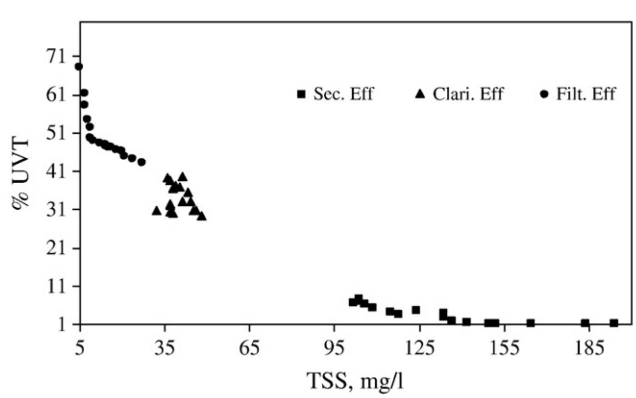

Fig. 4. Transmittance values vs. total suspended solids concentrations in the secondary, clarified, and filtered effluents.

The improved overall bacterial removal efficiency by prefiltration supports the hypothesis of bacteria associated with particles being protected from UV [6].

In the disinfection of the secondary, clarified and filtered effluents with a combination of LP and MP lamps simultaneously (Fig. 7), cumulative doses of 676, 694 and 537 mW s/cm^2, respectively, was required to reduce the target bacteria value to the standard level. Streptococcus faecalis was not detected in the filtered effluent with SOR < 630 L/m^2 h that was irradiated with a combination of MP and LP lamps at doses over 484 mW s/cm^2. This result apparently showed that in the clarified and filtered effluents, the MP lamp led to higher disinfection efficiency.

For post-media filtration UV systems, it is recommended that a UV design dose of at least 100 mJ/cm^2 and a design UV transmittance of 55% be required [18].

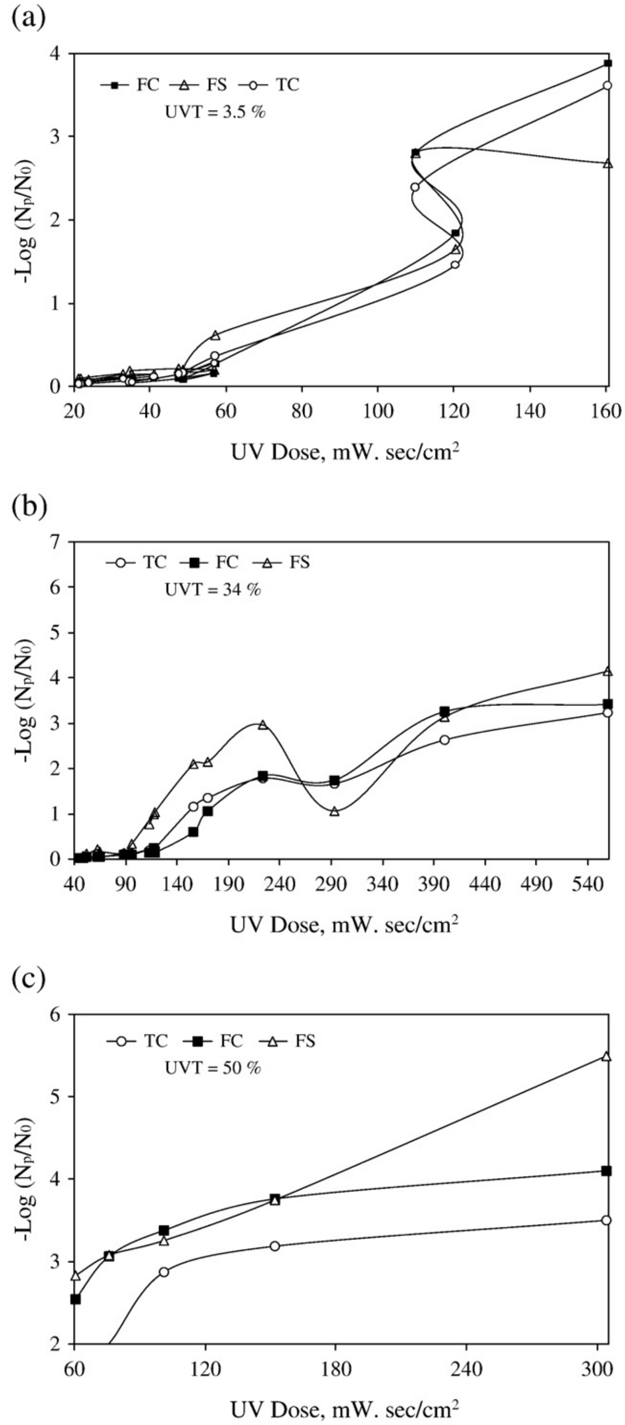

Fig. 5. Logarithmic inactivation of target bacteria vs. different doses of LP lamp for disinfection of (a) secondary, (b) clarified and (c) filtered effluents.

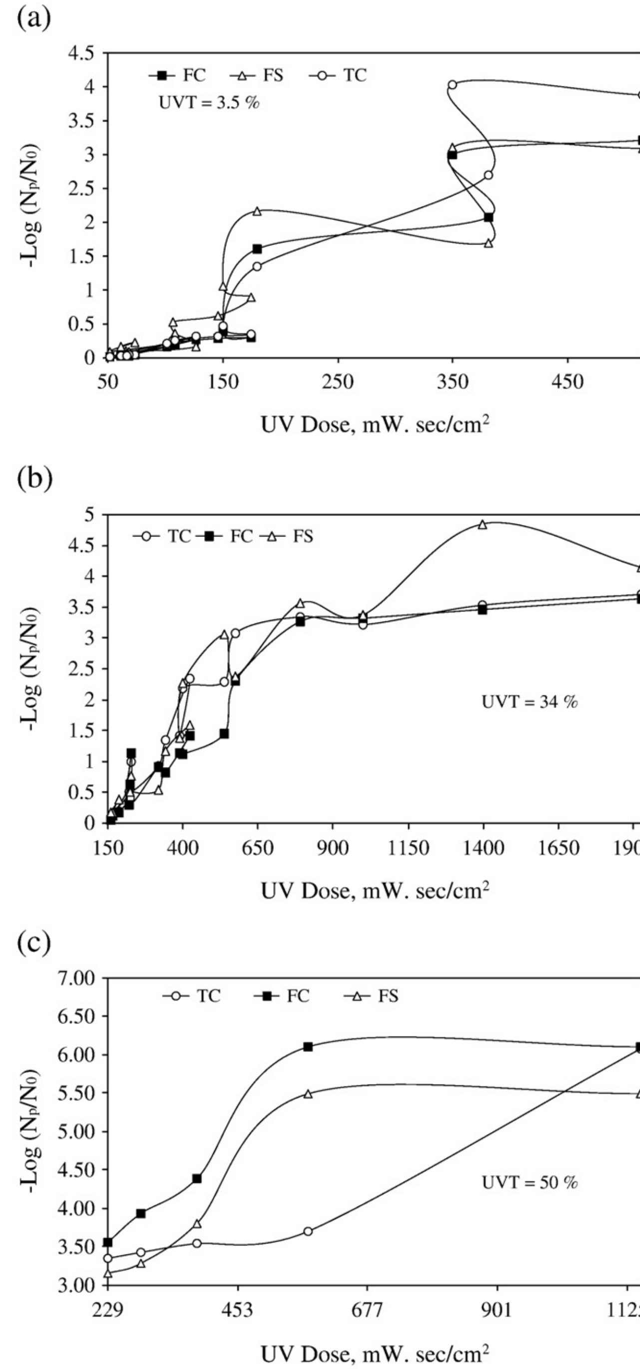

Fig. 6. Logarithmic inactivation of target bacteria vs. different doses of MP lamp for disinfection of (a) secondary, (b) clarified and (c) filtered effluents.

Note that Fig. 6c shows a log reduction of 3.2, whereas a reduction of 3.6 is required to meet the effluent standard with the MP lamp, based on the average influent total and fecal coliforms of 1.2×10^7 and 1.3×0^4 MPN/100 mL respectively. Log reduction of Streptococcus in this dose was 4.5.

In this circumstance, the TSS content of filtered effluent was 24 mg/L. Paired *t*-tests showed significant differences between bacterial concentrations in the effluent before and after UV disinfection (p-value$<$0/05); indicating that UV radiation was effective in reducing microbial load, although this reduction in some cases did not reach the standard limits.

In this study, the photo-reactivations of coliforms and Streptococcus after LP and MP exposure in the three alternatives were determined; after treatment with the MP lamp they were very much less than with the LP lamp. UV dose, transmittance and TSS contents led to different percentages of photo-reactivation in the three alternatives. The high UV doses were able to achieve only a 3.39–4.06 log reduction of total coliforms. Total inactivation of both fecal coliforms and E. coli has been achieved under the UV dose of 330 mJ/cm^2 [19]. According to recent studies, photo-reactivation percentages after LP and MP lamp treatments at a dose of 5 mJ/cm^2 were 50 and 20%, respectively. In this study, photo-reactivation of fecal Streptococcus was not seen to the same extent as in the study by Locas et al. [15].

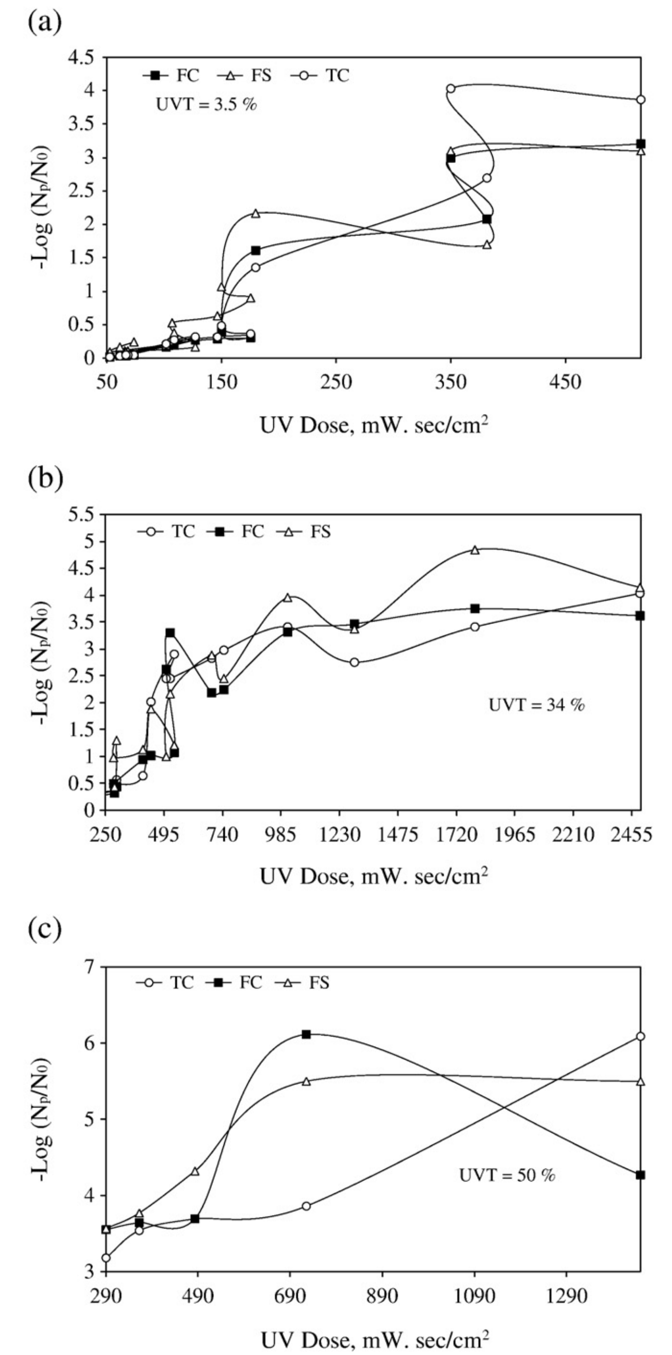

Fig. 7. Logarithmic inactivation of target bacteria vs. different doses of LP + MP lamps for disinfection of: (a) secondary, (b) clarified and (c) filtered effluents.

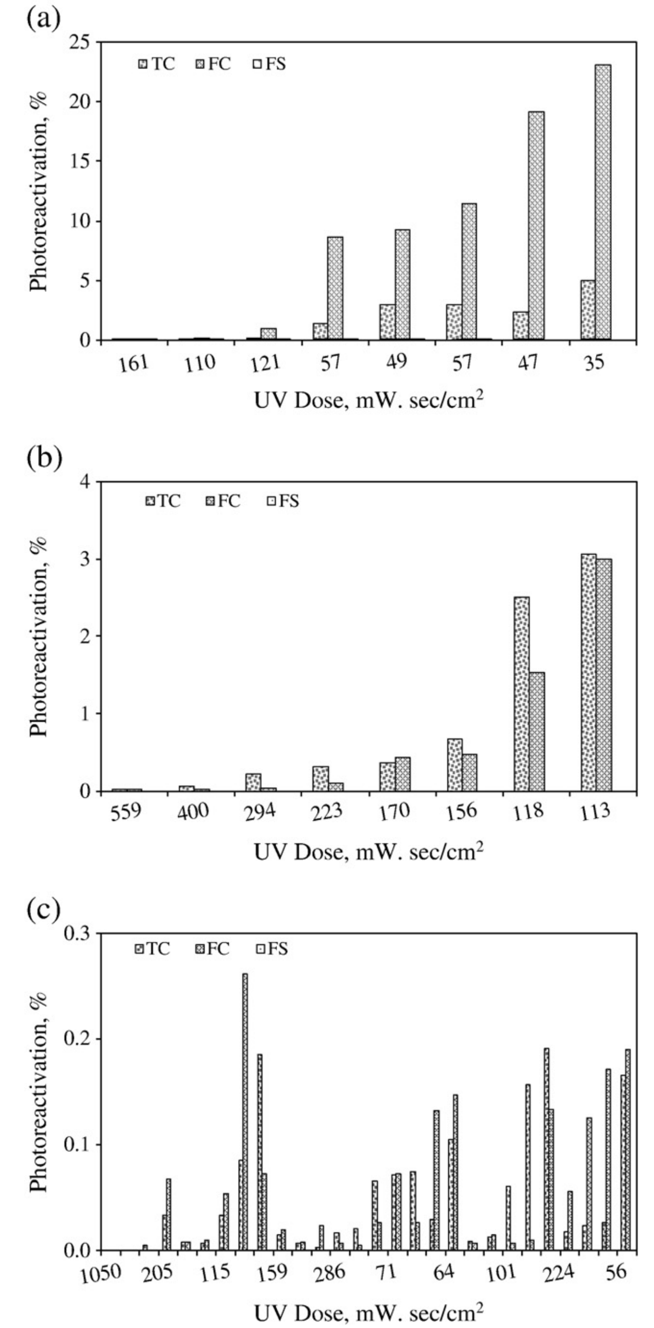

Fig. 8. Photo-reactivation of target bacteria for different doses of LP lamp after disinfection of (a) secondary, (b) clarified and (c) filtered effluents.

UV-disinfected samples showed no regrowth of fecal coliform bacteria by photo-reactivation or dark repair [9]. The results of bacterial photo-reactivation are shown in Figs. 8–10.

When a germicidal UV dose of 286 mJ/cm^2 was applied in this study, the percentage of photo-reactivation was 0.02% for the LP while regrowth was not seen after MP lamp exposure at this dose. It is clear that, for the same germicidal UV dose, a lower degree of photo-reactivation occurred after the MP exposure.

4.1. Lamp fouling study

Fouling materials are efficient absorbers of UV radiation, thereby diminishing the performance of radiation-based processes [20]. In wastewater treatment, the lamp fouling potential has been relatively high because of the high hardness values of secondary effluent (235 mg/L as $CaCO_3$) [12]. In this study, lamp cleaning was successful in restoring the measured UV intensity. The warm temperatures produced by UV lamps promote the precipitation of an inorganic, amorphous film on the surface of the quartz sleeves when the lamps are placed directly within the wastewater stream [10]. Mean values of total hardness in secondary, clarified and filtered effluents was 289, 249 and 214 mg/L, respectively, and effluent iron concentrations were 0.48, 0.72 and 0.32 mg/L, respectively. Although the amount of hardness and Fe in final effluents was quite low after clarification and filtration, a thin layer of hard deposits on the surface of quartz was still observed, especially in the MP reactors. The filtration led to a major reduction in the impurities and thus it may reduce the fouling of the UV lamps.

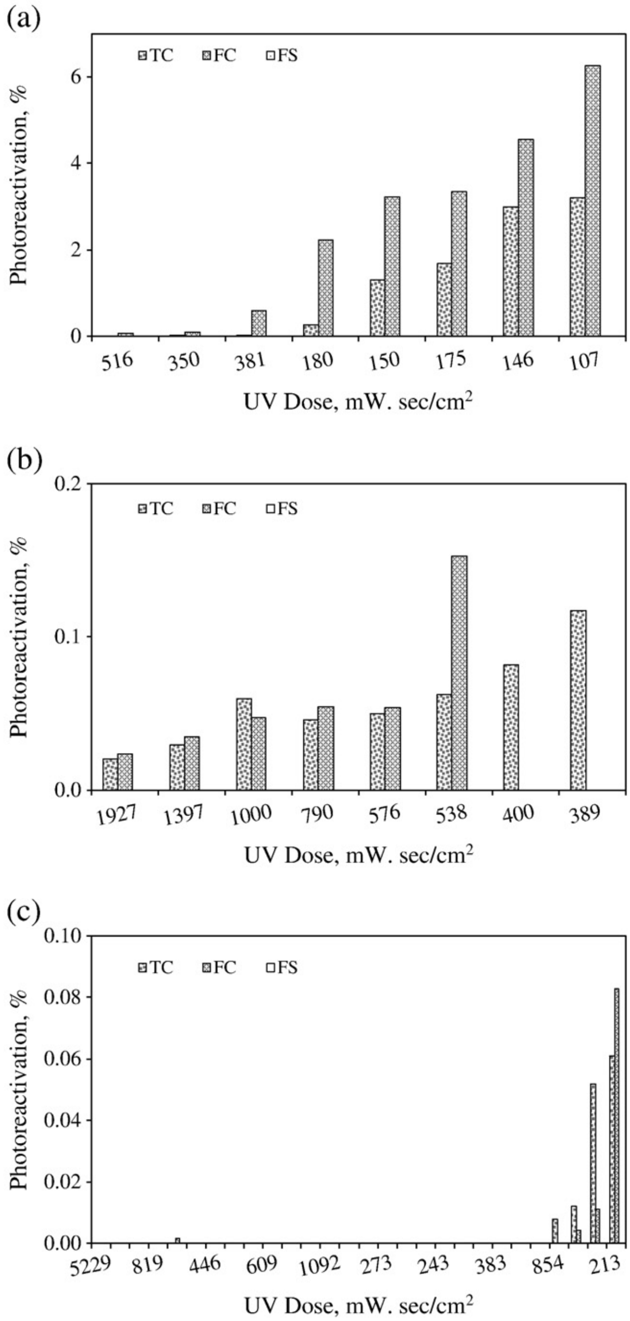

Fig. 9. Photo-reactivation of target bacteria for different doses of MP lamp after disinfection of (a) secondary, (b) clarified and (c) filtered effluents.

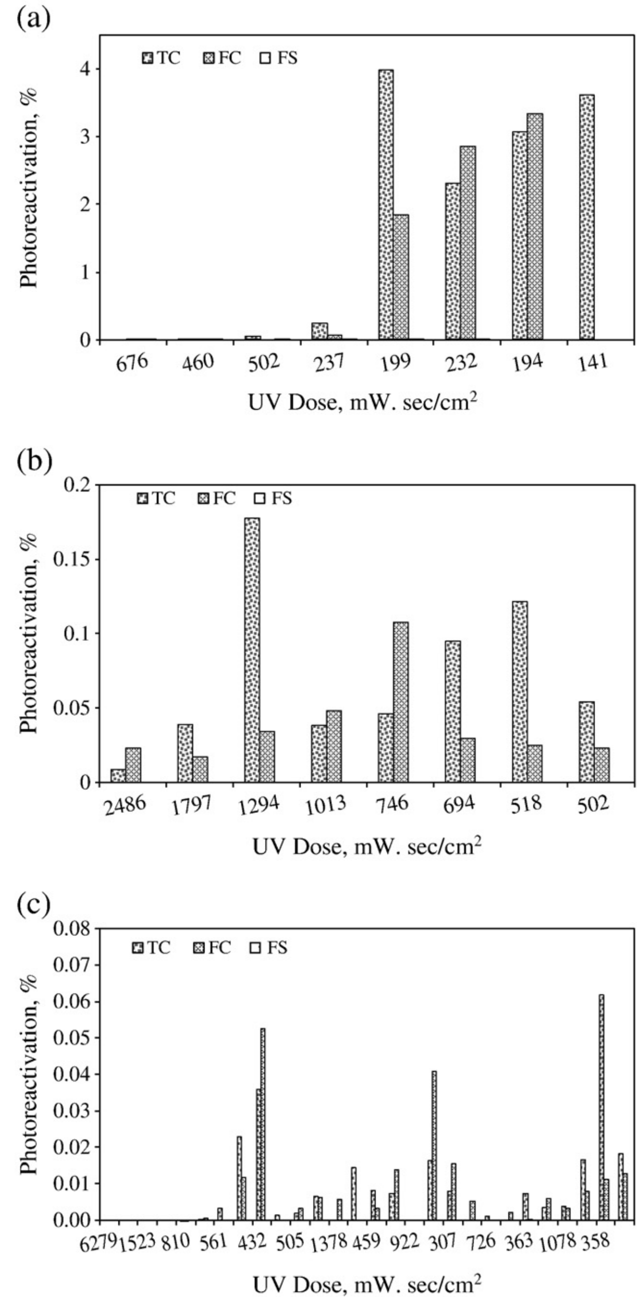

Fig. 10. Photo-reactivation of target bacteria for different doses of LP + MP lamps after disinfection of (a) secondary, (b) clarified and (c) filtered effluents.

5. Conclusions

Based on the results of this site-specific study, we concluded that the UV reactor was unable to improve the microbial quality of secondary wastewater effluent without pretreatment and this is related to the low transmittance of the effluent.

Disinfection of clarified and filtered effluents with the MP lamp in moderate to high doses is suitable for reducing the bacteria load down to the local standards for agricultural reuse. The filtration improved the microbiological and the physicochemical parameters, which enhanced the UV irradiation penetration. Statistical analysis using the ANOVA test demonstrated that there were significant differences among the log reduction of bacteria in the three alternatives (p-value < 0.05). Photo-reactivation and fouling occurred with both LP and MP reactors. However, a 15% regrowth with secondary effluent disinfection by LP was observed, while regrowth was only 0.03% with MP disinfection, after filtration. The pilot-plant experiments suggest that the planned tertiary treatment (filtration + MP lamp) could readily be converted into a full-scale installation at the investigated WWTP. In addition, filtration with a hydraulic loading of 1050 L/m^2 h followed by MP lamp exposure at a dose of 230 mW s/cm^2 (45 mW/cm^2 intensity and 5 sec exposure time) is an effective alternative to reduce the coliforms and Streptococcus counts in the secondary effluent sufficiently to meet the local standards for effluent discharge used for unrestricted agricultural irrigation. With regards to the existing chlorine contact chamber in the Isfahan North WWTP, installation of an open-channel UV system could result in a large saving of investment costs.

Symbols

α	absorptivity, cm^{-1}
d	irradiated sample depth, cm
D	UV Dose, (milli-watt second per square centimeter; mW·s/cm^2)
I_{avg}	Average UV Intensity, (milli-watt per square centimeter; mW/cm^2)
I_0	Initial UV Intensity, (milli-watt per square centimeter; mW/cm^2)
N_t	immediate survival after UV disinfection (MPN/100 mL)
N_0	initial bacterial number (MPN/100 mL)
N_p	cell number of photoreactivated sample (MPN/100 mL)
K	inactivation rate constant (cm^2/mW s)
t	exposure time (second)
P(%)	photo-reactivation percentage
V	reactor volume (liter)
Q	flowrate (liter per second)

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