Disinfection of an advanced primary effluent using peracetic acid or ultraviolet radiation for its reuse in public services

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ABSTRACT

The disinfection of a continuous flow of an effluent from an advanced primary treatment (coagulation-flocculation-sedimentation) with or without posterior filtration, using either peracetic acid (PAA) or ultraviolet (UV) radiation was studied. We aimed to obtain bacteriological quality to comply with the microbiological standard established in the Mexican regulations for treated wastewater reuse (NOM-003-SEMARNAT-1997), i.e., less than 240 MPN (most probable number) FC/100 mL. The concentrations of PAA were 10, 15, and 20 mg/L, with contact times of 10, and 15 min. Fecal coliforms (FC) inactivation ranged from 0.93 up to 6.4 log units, and in all cases it reached the limits set by the mentioned regulation. Water quality influenced the PAA disinfection effectiveness. An efficiency of 91% was achieved for the unfiltered effluent, as compared to 99% when wastewater was filtered. UV radiation was applied to wastewater flows of 21, 30 and 39 L/min, with dosages from 1 to 6 mJ/cm². This treatment did not achieve the bacteriological quality required for treated wastewater reuse, since the best inactivation of FC was 1.62 log units, for a flow of 21 L/min of filtered wastewater and a UV dosage of 5.6 mJ/cm².

Key words | advanced primary treatment, disinfection, fecal coliforms, peracetic acid, ultraviolet radiation

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INTRODUCTION

Treated wastewater reuse has become an attractive alternative in cities where potable water is scarce. However, pathogens persisting after treatment pose a significant threat to human health. Therefore, special care should be taken in providing the adequate levels of disinfection required by present regulations.

Chlorine, the most commonly used disinfectant, generates disinfection by-products that cause several adverse health effects (Liberti & Notarnicola 1999; Monarca et al. 2000; Chowdhury et al. 2011). Alternative processes with little or non-risky by-products, such as peracetic acid (PAA) and ultraviolet (UV) radiation that can be as economical and effective as chlorine, have been developed (Liberti et al. 2003; Kitis 2004). Reductions ranging from 3.21 to 4.21 log total coliforms (TC) have been observed when applying up to 8 mg/L PAA to a filtered secondary effluent in batch studies (Caretti & Lubello 2003); disinfection of advanced primary treated wastewaters with an average UV fluence of 10 mJ/cm² produced average fecal coliforms (FC) reductions of 2.2 log in batch reactors (Maya et al. 2003). Gonzalez et al. (2012) reported an efficiency germicidal effect of around 5 log using a PAA/UV process, when dosing 30 mg PAA/L at a continuous pilot plant flow of 21 L/min and contact time of 10 min to attain an average $C_t \cdot t$ product (where Ct indicates the residual PAA concentration after contact time t) of 24.2 mg min/L, and an average UV fluence of 13 mJ/cm².

However, it has been pointed out that the quality of treated wastewater may have an important effect on the immediate PAA demand (Gehr *et al.* 2003) and suspended solids have an adverse effect on disinfection efficiency particularly for UV processes (Loge *et al.* 2001). Previous works have demonstrated that some microorganisms entrapped into suspended solids can survive different disinfection processes, but very scarce work has been done in continuous-flow units (NOM-003-SEMARNAT-1997, APHA *et al.* 2005; Winward *et al.* 2008). Therefore we aimed to investigate the influence of the presence or absence of suspended solids on the disinfection efficiency when applying these processes to a continuous advanced primary treatment effluent. This study focused on evaluating an alternative disinfection process (PAA or UV) to the continuous flow of an effluent produced from an advanced primary treatment process (coagulation-flocculation-sedimentation) with or without filtration, aiming to comply with the microbiological standard established by the Mexican regulations for treated wastewater reuse in public services, for irrigation of landscape and recreational areas (NOM-003-SEMARNAT-1997), i.e., less than 240 MPN (most probable number) FC/100 mL. This meant achieving reductions of up to 5 log, considering initial concentrations from 4.01 to 4.37×10^6 CFU (colony-forming units)/100 mL.

METHODOLOGY

Water quality tests

Water quality was determined using the techniques indicated in Table 1. Spectrophotometry analyses, including

Table 1 | Water quality analytical methods

Parameter	Technique
pH	4500 B (H^+) method (APHA *et al.* 2005)
Turbidity	2130 B method (APHA *et al.* 2005)
Total suspended solids	Hach method 8006 (Hach 2005)
Chemical oxygen demand	Hach method 8000 (Hach 2005)
Total and FC	ISO method 9308/1
Residual PAA	DPD method (Falsanisi *et al.* 2006)

UV transmittance at 254 nm, were conducted with a Varian Cary 50 spectrophotometer; pH was measured with an Orion 290a Portable Meter; colorimetric analyses were carried out using a HACH DR/890 colorimeter.

The membrane filter method was used to quantify TC, grown in M-ENDO agar. TC were incubated at $35\,°C \pm 2$ for 24 h; whereas FC were quantified in MFC medium, and incubated in a water bath at $44.5\,°C \pm 2$ also for 24 h.

Pilot wastewater treatment and disinfection units

Continuous flow tests were conducted at a water resource recovery facility located at the Metropolitan Autonomous University, Azcapotzalco Campus, Mexico City, designed to treat 30 L/min (mean design flow). Pre-treated wastewater (screened and grit removed) was pumped to a rapid mixing unit where alum was added (dose: 110 mg/L). Flocculation with 2.4 mg/L of cationic polyelectrolyte takes place in two serial chambers, equipped with hydrofoil variable speed mixers, followed by a high rate settling unit and a storage unit prior to disinfection.

The selected disinfectants for these experiments were PAA and UV irradiation which were separately applied. A diaphragm dosing-pump was used to feed PAA (DEGUSA, Co.) to a static mixer, located ahead of the UV disinfection unit. UV equipment was an InLine 20 Berson/Aquionics model, with a 316 L stainless steel irradiation chamber, and a B410 Multiwave® high intensity medium pressure UV-lamp (72.4 W, normalized UVC, UV radiation, subtype C, output 240–320 nmn), perpendicular to the flow and enclosed inside a quartz sleeve. Wastewater was alternatively filtered through an anthracite column followed by a microfiltration unit.

Laboratory tests

Laboratory disinfection tests using PAA, and residual PAA measurements were carried out following the procedures described by Falsanisi *et al.* (2006). The germicidal effect of the chemical agent was measured as a function of contact time. Three different initial concentrations of oxidant (10, 15, and 20 mg PAA/L) were tested.

The microbial inactivation level (germicidal effect) was expressed in logarithmic units (log), as $I = -\log (N/N_0)$,

where I: microbial inactivation level, log; N_0: initial microorganisms count at the beginning of the test, CFU/100 mL and N: remaining microorganisms at the end of the test, CFU/100 mL. The efficiency of the process (η) is expressed as the percentage of the remaining microorganisms with respect to the initial concentration.

The UV irradiation disinfection effect was initially measured in the laboratory based on procedures for collimated beam (CB) tests as described by Bolton & Linden (2003) to obtain CB standardized curves, which were approximated by means of the logistic model, as suggested by Gehr et al. (2003). UV irradiation was measured with an IL1400B International Light Technologies (ILT) radiometer, and an ILT SEL240/NS254/TD UV detector.

Continuous flow tests

Two experimental sets were carried out during the continuous flow tests: one to evaluate the effect of PAA addition; another to measure the UV disinfection performance.

For the PAA germicidal continuous flow tests, a twelve-treatment experiment run in triplicate was used. TC and FC counts were used as the response variables.

To measure microbial inactivation level (in logarithmic units) when UV irradiation was utilized in the wastewater treatment pilot plant, a two-condition (filtered and unfiltered samples), three-level design experiment run in triplicate was carried out. UV exposure time was inversely proportional to operating flow yielding three different test conditions: low, medium, and high flow; then, the resulting average UV fluence to which microorganisms were exposed, was estimated from the standardized CB curves (Falsanisi et al. 2006).

RESULTS AND DISCUSSION

Wastewater quality for continuous flow pilot plant tests

The average water quality of the settling tank effluent after the advanced primary coagulation, used in the continuous flow disinfection tests, with and without filtration is presented in Table 2. It can be observed that, after filtration, 93.0% turbidity, 93.7% suspended solids and 34.6% of the

Table 2 | Quality of treated wastewater before disinfection

Parameter	Average value	
	Unfiltered	Filtered
TC (CFU/100 mL)	$7.35 \pm 0.43 \times 10^6$	$7.24 \pm 1.44 \times 10^6$
FC (CFU/100 mL)	$4.34 \pm 0.90 \times 10^6$	$4.01 \pm 0.77 \times 10^6$
Turbidity (NTU)	23.85 ± 4.08	1.66 ± 0.48
pH	6.90 ± 0.15	6.87 ± 0.33
COD (mg/L)	112.08 ± 53.64	73.25 ± 17.81
TSS (mg/L)	15.08 ± 3.20	0.95 ± 0.87

TSS: total suspended solids, NTU: nephelometric turbidity units.

organic matter, determined as chemical oxygen demand (COD), were removed. TC, FC, and pH, remained nearly unchanged.

PAA disinfection: continuous flow pilot plant tests

A factorial experiment setting initial concentrations of PAA to 10, 15, and 30 mg PAA/L, and contact times of 5, 10, and 15 min, with unfiltered and filtered wastewater was performed. Residual PAA was measured after the contact time, and then $C_t \cdot t$ product (where Ct indicates the residual PAA concentration after contact time t) was calculated. Analysis of variance (ANOVA) for this test resulted in a P-value of the F-test under 0.05, and therefore there was a statistically significant difference between the means of the treatments at the 95.0% confidence level. The disinfection efficiency (η) as a function of PAA concentration, ranged between 88 and 98% (Figure 1). With respect to contact time, this efficiency ranged between 89 and 99% (Figure 2). It was therefore proved that, water quality, regarding suspended solids present or removed by filtration, had an effect on efficiency, from 91% for the unfiltered effluent, to 99% when wastewater was filtered (Figure 3).

To comply with the current regulations, i.e., less than 240 MPN FC/100 mL, log reductions of the studied wastewater are listed, as observed in Table 3.

Coliforms inactivation achieved in the PAA experiments are summarized in Table 4. In all cases, after 15 min of contact time with any PAA concentrations ranging from 10 to 20 mg/L, TC and FC inactivation in both filtered and unfiltered wastewater complied with the requirements of the current regulation. Thus, this disinfectant represents a very
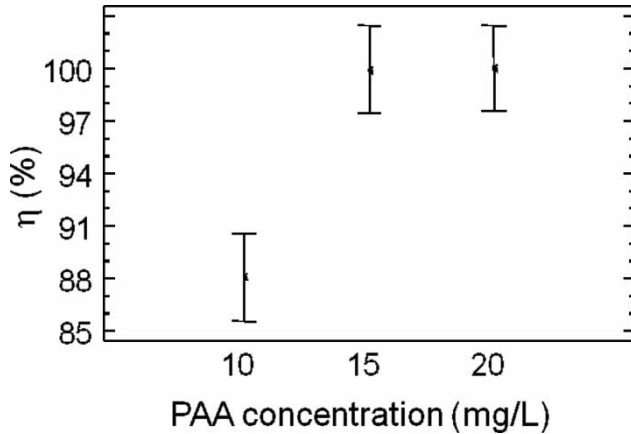
Figure 1 │ Disinfection efficiency as a function of PAA concentration in continuous flow experiments (95.0% confidence interval and contact time of 15 minutes).
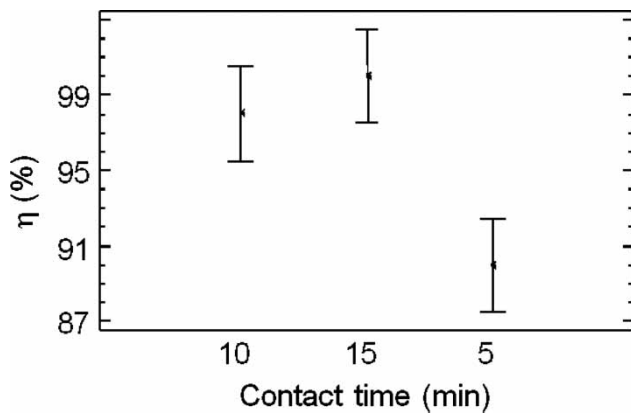

Figure 2 │ PAA disinfection efficiency as a function of contact time in continuous flow experiments, for a constant concentration of 15 mg/L, 95.0% confidence interval.
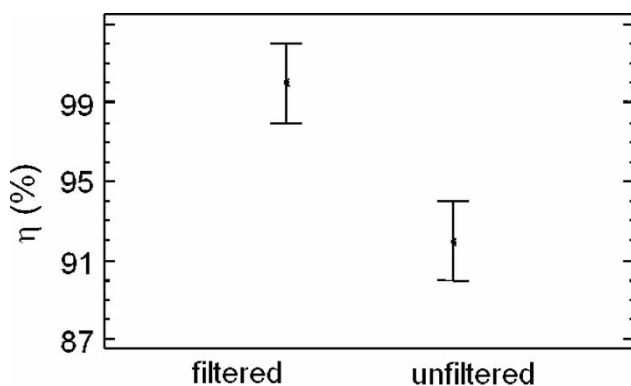

Figure 3 │ PAA disinfection efficiency as a function of water quality in continuous flow experiments, 15 minutes contact time and 15 mg/L PAA, 95.0% confidence interval.

Table 3 │ Disinfection and inactivation efficiencies to comply with current wastewater reuse regulations (NOM- 003-SEMARNAT-1997)

	Direct contact wastewater reuse		Indirect contact wastewater reuse	
	Inactivation (log unit)	Disinfection η (%)	Inactivation (log unit)	Disinfection η (%)
FC	4.3	99.995	3.6	99.977
TC	4.5	99.997	3.9	99.986

attractive option to substitute the risks related to chlorine disinfection.

These results are comparable to those reported by Chen *et al.* (2005) who utilized a similar treated effluent from a water resource recovery facility in Montreal, using an advanced primary treatment, where particulate matter ranged from 17 to 28 mg TSS/L, and COD ranged from 67 to 132 mg/L. These authors reported FC inactivation that fluctuated from 3 to 4 log when 2 to 4 mg PAA/L was added, for a 30 min contact time in batch tests. Moreover, Mezzanotte *et al.* (2003) achieved TC inactivation efficiencies from 2 to 4 log, when they added 15 mg PAA/L and maintained 12 to 30 min contact times using wastewater from a secondary process in Milan, followed by rapid sand filtration. TSS concentration ranged from 3 to 24 mg/L, and COD from 4 to 97 mg/L.

UV irradiation disinfection in the continuous flow pilot plant tests

Continuous flow UV irradiation tests were carried out with a UV fluence of 2.7, 2.87 and 3.26 mJ/cm^2, which corresponded to operating flows (Q) of the wastewater treatment pilot plant of 21, 30, and 39 L/min. ANOVA results for this experiment (P-value $<10^{-4}$) showed that there was a statistically significant difference between the means of the three treatments at the 95.0% confidence level. Remaining coliform levels are presented in Tables 5 and 6.

It was observed that the inactivation improved as the flow became slower, within the allowance of the UV lamp operation. In both filtered and unfiltered wastewaters, UV disinfection could only achieve less than 2 log unit reductions, and this may imply that the quality of the wastewater has no significant influence on the process. In no case

Table 4 | Total and FC inactivation after PAA disinfection

PAA (mg/L)	Inactivation of TC (log units)						Inactivation of FC (log units)					
	Unfiltered			Filtered			Unfiltered			Filtered		
	5 min	10 min	15 min	5 min	10 min	15 min	5 min	10 min	15 min	5 min	10 min	15 min
10	0.22	0.93	4.32	3.70	4.47	4.90	0.61	0.93	4.30	3.82	4.58	5.15
15	2.29	3.02	4.91	4.85	5.27	6.25	2.45	3.02	4.79	4.82	6.12	5.43
20	3.32	4.05	5.07	5.24	6.55	6.11	3.33	4.02	5.07	5.77	6.43	6.43

Initial TC (CFU/100 mL) Unfiltered: $7.35 \pm 0.43 \times 10^6$; Filtered: $7.24 \pm 1.44 \times 10^6$.
Initial FC (CFU/100 mL) Unfiltered: $4.34 \pm 0.90 \times 10^6$; Filtered: $4.01 \pm 0.77 \times 10^6$.

Table 5 | TC remaining after UV disinfection

Operating flow (L/min)	Unfiltered			Filtered		
	TC			TC		
	(CFU/100 mL)	(Log units)	UV fluence (mJ/cm^2)	(CFU/100 mL)	(Log units)	UV fluence (mJ/cm^2)
Blank	8.53×10^6		0.00	2.03×10^6		0.00
21	4.75×10^5	1.26	3.26	3.88×10^4	1.73	8.59
30	6.61×10^5	1.11	2.87	8.17×10^4	1.44	6.41
39	7.83×10^5	1.02	2.70	1.84×10^5	1.05	4.71

Table 6 | FC remaining after UV disinfection

Q (L/min)	Unfiltered			Filtered		
	FC			FC		
	(CFU/100 mL)	(Log units)	UV fluence (mJ/cm^2)	(CFU/100 mL)	(Log units)	UV fluence (mJ/cm^2)
Blank	5.01×10^6	0.00	0.00	1.01×10^6	0	0.00
21	2.67×10^5	1.28	2.32	2.44×10^4	1.62	5.56
30	3.62×10^5	1.14	2.07	4.55×10^4	1.37	4.51
39	4.37×10^5	1.06	1.93	1.06×10^5	0.99	3.29

did the UV disinfected wastewater comply with the current regulation.

Costs estimation for conventional and alternative disinfectant processes

Costs represent an important factor that might influence the implementation of an alternative disinfection process.

The costs of the chlorine disinfection systems depend on the manufacturer, and the plant location and capacity, as well as the characteristics of the wastewater to be treated. For example, hypochlorite compounds tend to be more expensive than chlorine gas (see Table 7). Despite this, several large cities have adopted the use of hypochlorite in order to avoid transportation through urban areas. Besides the chlorination costs, in some cases dechlorination costs also have to be taken into account, since they increase

Table 7 | Comparative synthesis, results obtained and cost of different disinfectants applied to an advanced primary treatment

Disinfectant	Microorganisms	Dose	Time (min)	Disinfection method	Costs USD[a]/m³	Reference
Conventional disinfectants						
Physical methods						
UV	FC	100–160 mWs/cm²	0.5	Gamma Beams	0.0427	Liberti *et al.* (2000)
Chemical methods						
Chlorine	FC	5–20 (mg/L)	15–30	Hypochlorite	0.0547	Rojas-Valencia *et al.* (2012)
				Chlorine	0.0292	
				Chlorine	0.0405	EPA (1999a)
Non-conventional disinfectants						
Chemical methods						
PAA	FC	400 (mg/L)	20	Chemical	3.147	Liberti *et al.* (2000)

[a]USD: United States Dollars.

total disinfection costs by 30–50% (Environmental Protection Agency (EPA) 1999b).

Currently, chlorination is more attractive in terms of costs (28.14 USD/1000 m³ or 0.028 USD/m³) than UV radiation, except when dechlorination is needed, which increases the cost to 0.0427 USD/m³. The annual operating and maintenance costs for chlorine disinfection include electric energy consumption, chemical compounds and cleaning materials, and equipment repair, as well as labor expenses.

The cost of UV light disinfection systems depends on the manufacturer, the location and capacity of the plant, and the characteristics of the wastewater to be disinfected. The cost based on data obtained by Liberti *et al.* (2000) with 100 to 160 mWs/cm² in an advanced primary treatment to obtain a 5 log coliform reduction is 42.7 USD/1000 m³ or 0.043 USD/m³.

With regard to the non-conventional chemical disinfectants costs, there is only an estimate at laboratory level for reagents use. A calculation of the reagent grade (DEGUSA) PAA costs gives a value of 3.147 USD/m³. Obvious reductions could be expected if the process was commercially implemented, since its effectiveness has been demonstrated.

To compare costs, contact times and log reduction of each disinfectant, a dose has to be defined. The doses needed to achieve microorganism inactivation vary significantly from one disinfectant to another, even among microorganisms upon applying the same disinfectant (see Table 7).

UV is becoming quite competitive in term of costs and, in spite of the fact that in the present study the technology was not suitable to attain the expected disinfection standards, it might be used as a preliminary or posterior process in combined systems with competitive costs (Gehr *et al.* 2003; Gonzalez *et al.* 2012).

CONCLUSIONS

The disinfection level required by Mexican water-reuse legislation could be achieved when the PAA disinfection process is used; a FC concentration of less than 240 MPN/100 mL would be consistently attained from the disinfection of a filtered or unfiltered advanced primary treated effluent.

In the current case study, it was observed that a PAA dose was highly effective at inactivating TC, generating reductions ranging from 1 to 5 log, while UV fluence of up to 3.26 mJ/cm² was less effective and achieved inactivation ranging from 1.5 to 2.5 log.

A 5.1 log TC and FC reduction was attained when the PAA disinfection process was utilized. Doses ranging from 10 to 20 mg PAA/L and up to 15 min contact times were applied.

Water quality influenced the PAA disinfection effectiveness. An efficiency of 91% was achieved for the unfiltered effluent, as compared to 99% when wastewater was filtered.

Although chlorine disinfection is still considered an affordable process, the emerging technologies may soon

reach competitive costs, as they have been proven techni-
cally effective.

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