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Disinfection of Primary Municipal Wastewater Effluents Using Continuous UV and Ozone Treatment

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ABSTRACT

UV radiation and ozonation were investigated as disinfection alternatives for the wastewater treatment plant. The inactivation of total and fecal coliforms using ozone and ultraviolet radiation as separate treatments was evaluated. Different ozone concentrations (3 to 40 mg O_3/L) were applied and UV fluencies ranging from 8.5 to 12 mJ/cm^2 at different pH values (from 5 to 9) were tested. Best results were obtained for ozone doses near 20 mg/min with removals of 72% and 78% of fecal and total coliforms, respectively. The ozone also was capable of oxidizing organic matter in the effluent measured as COD (the highest removal obtained was 36% for 20 mg O_3/min). Maximum bacterial resistance was observed at pH 7 in both cases. The UV light offered a high bacterial inactivation (over 80%) and the lowest bacterial inactivation was observed at pH 7. Finally, we obtained the electric energy per order (E_{EO}, kWh/m^3/order), defined as the electric energy (kW-h) required to degrade a contaminant by one order of magnitude in a unit volume of contaminated water, being noteworthy that E_{EO} values for the UV process resulted were lower than those determined for the process with ozone in all the water flow tested.

KEYWORDS

Disinfection; Ozone Treatment; UV Treatment; Wastewater

1. Introduction

Water availability is a complex issue worldwide, mainly in regions with high population density and low rainfall. It is a well-known fact that the water quality of many water supply sources is at high risk of deterioration due to discharges of poorly treated or untreated wastewater. As a result of the depletion on water quality, the incidence of waterborne illnesses has increased in the last decade, representing up to 13% of the 15 million deaths caused by infection diseases worldwide [1]. Children under the age of five represent the population sector (75%) most impacted by this phenomenon, mainly in developing countries.

Municipal wastewater has been identified as one of the main sources of pathogenic agents and the potential vector of diseases as a result of accidental consumption of untreated or poorly treated wastewater, skin contact or ingestion of food species exposed to wastewater. Hence, disinfection of wastewater is mandatory as the minimum treatment before their release to natural water streams. Chlorination is one of the most widely used disinfection processes for water treatment due to its high efficiency and low cost [2]. Nevertheless, in the case of wastewater, chlorination is probably not the best choice due to its well-known potential to react with organic matter present in municipal effluents and generate disinfection by-products which are animal carcinogens and suspected human carcinogens [3,4].

Among the different alternatives to chorine disinfection, UV radiation and ozone have emerged in the last years as competitive procedures for generating safe drinking water from raw surface or underground water [5]. Application of UV radiation for the disinfection of wastewater is a scientific task which has recently been explored. The number of facilities using UV disinfection has augmented in the last years and it is expected to keep increasing in the next years [2,4,6]. Ozone, on the other hand, has been described as an efficient disinfection agent, able not only to control bacteria, but also to oxidize organic matter in municipal effluents [7]. However, despite its high potential for application in municipal effluent, relatively few papers dealing with this approach have been reported [8,9].

The aim of this work is to present the application of ozone and UV radiation in the disinfection and oxidation of organic matter of an effluent produced from an advanced primary treatment process and to evaluate their potential use (separately or jointly) as a polishing step for the generation of an affordable effluent for safe reuse or release into the environment. We also proposed the use of scale-up parameter and the energy required to achieve the disinfection goals of each of the processes applied to compare their performance.

2. Methods

2.1. Wastewater Sampling and Characterization

Disinfection studies were run at the wastewater treatment plant (WTP) located at the Autonomous Metropolitan University—Azcapotzalco campus in Mexico City. The WTP includes a physical chemical treatment train and it was designed to process up to 1 L/s as maximum wastewater flow. The treatment train includes a coagulation-flocculation step, followed by settling and filtration. In order to obtain the quality parameters of the influent a thorough sampling was performed. As required by the Mexican regulation [10], subsamples were taken from the effluent every 4 hours during a 24-h period and the effluent flow was measured for every sampling time. A composite sample was prepared with proportions based on the water flow determined on every period. The wastewater sample was characterized for different physical-chemical (chemical oxygen demand, COD; turbidity; total suspended solid, TSS; pH) and microbiological (total and fecal coliforms) parameters following the standard membrane methodologies [11], before applying the disinfection procedures after the settling tank.

Flow-chart of wastewater advanced primary treatment and Ozone-UV disinfection is presented in **Figure 1**.

2.2. Wastewater Disinfection Assessments

UV wastewater disinfection experiments were carried out on line after the settling tank using a collimated UV radiation (254 nm wavelength) equipment (International Light Technologies, Mod. IL 1400BL) equipped with a UV radiometer (International Light Technologies, Mod. SEL 240/NS254/TD). Different contact times were tested by varying the water flow (0.16, 0.32 and 0.5 L/s) through the UV disinfection equipment; the total radiant energy was controlled by the pump rate. Two different fluencies (8.5 and 12 mJ/cm^2), corresponding to 15 and 30 L/min, respectively, were tested. Different pH values (from 5 to 9), adjusted with H_2SO_4 (0.5 M) or NaOH (0.5 M), depending on the desired initial pH value, were also assessed to determine the influence of this parameter on the disinfection efficiency.

An ozone generator (Ozone Ecological) connected on line, coupled to a 3-HP air compressor (Craftsman), was used in the ozone disinfection experiments. Different ozone concentrations (3 to 40 mg O_3/L) were tested at the same flows described for UV tests, and different pH values (from 5 to 9) were tested, adjusting with H_2SO_4 (0.5 M) or NaOH (0.5 M) depending on the desired initial pH value.

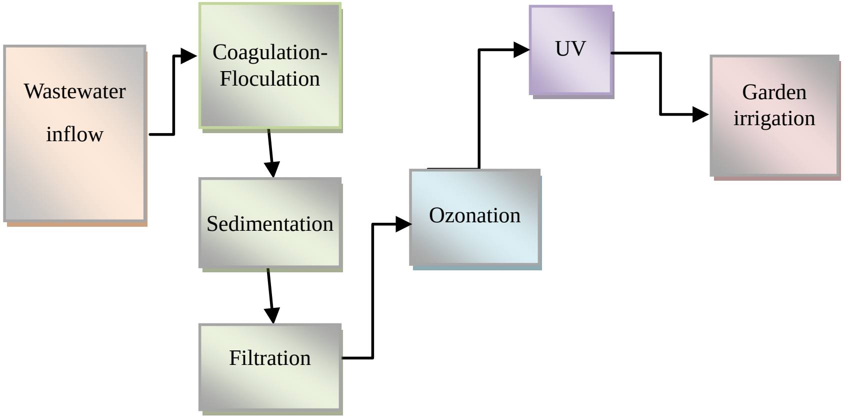

Figure 1. **Flow-chart of wastewater advanced primary treatment and Ozone-UV disinfection.**

2.3. Analytical Measurements

Samples were taken before and after every disinfection procedure in order to determine the efficiency of the tested methodology. In the case of UV-radiation disinfection, total and fecal coliforms (as CFU/100 mL) were used to monitor the process. For ozone treatment, besides the microbiological measurements, the oxidation of organic matter as COD measurements before and after the treatment was also measured. Total suspended solids (TSS), pH and temperature were determined in every experimental run before and after the treatment.

3. Results and Discussion

3.1. Wastewater Characterization

The results of the initial wastewater characterization of the composite sample obtained after the settling tank in the WTP effluent are presented in **Table 1**. High concentration values of total and fecal coliforms and COD in the sample were observed. This implied that, despite the physical-chemical treatment originally applied to the municipal wastewater, the produced effluent was not ready to be released to the environment without posing a significant risk of contamination of surface or underground water. The observed amounts of total and fecal coliforms, 5.0×10^6 and 1.0×10^6 CFU (colony-forming units), respectively, were comparable to those previously reported for raw wastewater to which no treatment had been applied [12,13].

Besides, the value obtained for total coliforms agreed with previous reports on the concentration of these microbiological indexes in secondary effluents in other parts of Mexico [14,15]. COD concentration was slightly higher than the maximum acceptable limit in Mexican legislation for treated wastewater meant for all re-uses (150 mg/L, as stated in NOM-001-SEMARNAT-1996). TSS values (11.63 *vs*. 150 mg/L) and pH values were within the limits set by Mexican legislation. These results suggested that, even though the process was efficient in removing most of the suspended solids, an important portion of the dissolved solids (as organic matter) and much of the bacteria passed through the water treatment and remained in the effluent.

Table 1. Parameters of quality of the water to be disinfected.

Parameter	Value
COD, mg/L	154.6 ± 6.04
Turbidity, UT	17.49 ± 1.07
TSS, mg/L	11.63 ± 0.88
pH	6.69 ± 0.04
Conductivity, NTU	1880 ± 122
Alcalinity, mg/L as $CaCO_3$	164.31± 3.27
Total Kjeldahl nitrogen, mg/L	42.65 ± 2.51
Total phosphorus, mg/L	1.60 ± 0.45
Total coliforms, CFU/100 mL	5.0×10^6
Fecal coliforms, CFU/100 mL	1.0×10^6

3.2. UV Disinfection Assessments

The results for total and fecal coliforms (TC and FC, respectively) inactivation under different fluency and pH values are presented in **Figure 2**. As expected, no inactivation of microorganisms was achieved during experiments where no UV radiation was used and high bacteria inactivation (over 80%) was observed after the use of UV radiation.

It is worthy to note that fecal coliforms were less affected by the increase in energy fluence than total coliforms. These results agreed with previous reports where 90% - 99% of *E. coli* inactivation was reached using 5.4 and 8.1 mJ/cm^2, respectively to avoid photoreactivation [16]. Other authors have reported UV doses as high as 35 mJ/cm^2, for complete fecal coliforms inactivation, in the presence of high TSS concentrations (up to 40 mg/L) in wastewater [17].

The same trend was observed for different pH values tested (**Figure 3**). Inactivation rates were higher for total coliforms than fecal coliforms at all pH values tested. The maximum bacterial resistance was observed at about pH 7. Completely different results were found at acid or alkaline values. Under acidic conditions, due to changes in H^+ ions permeability at lower pH (pH = 5), bacterial cells should adjust the influx or efflux of H^+ with the

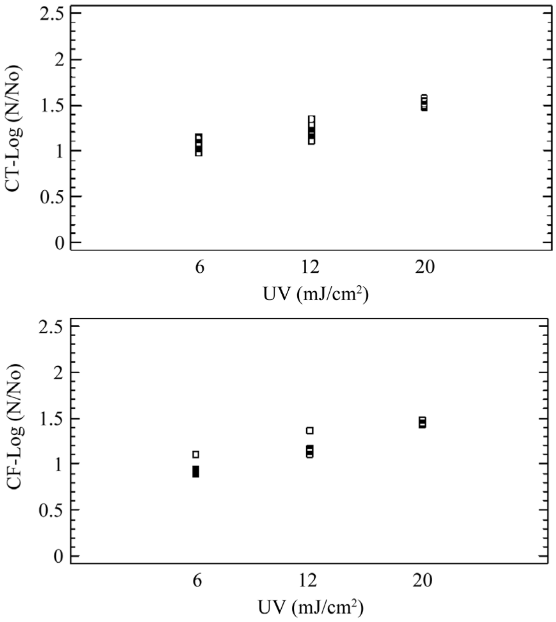

Figure 2. Inactivation of total (TC) and fecal (FC) coliforms with UV light.

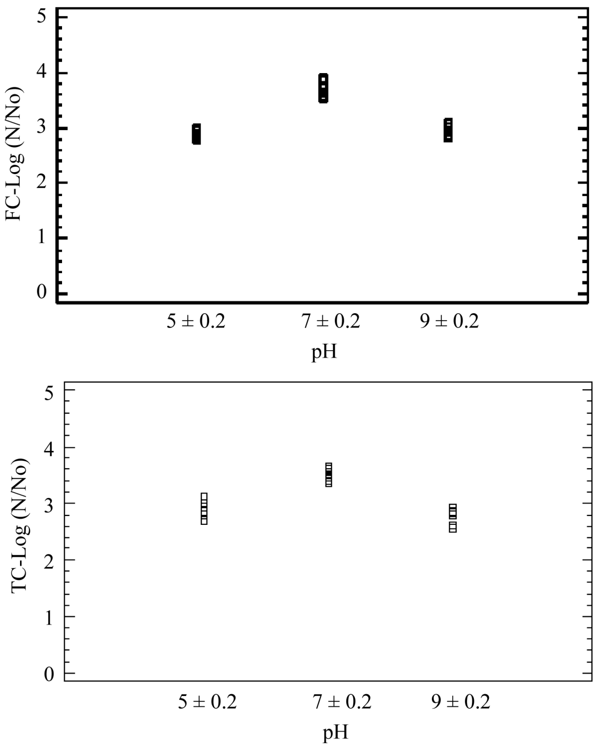

Figure 3. Inactivation of total and fecal coliforms (TC and FC) at different pH values.

change of pH value from 7 to 5 to maintain the homeostasis of the cell [16]. It is known that, when a sudden change of pH from neutral to acidic environment occurs, *E. coli* induces the synthesis of cyclopropane fatty acids (CFAs). This reduces H^+ ion permeability influx and increases its efflux [18]. This synthesis takes few minutes to induce and start to form these compounds and it is possible that the rate of synthesis of the new compounds that can protect the cells is not fast enough.

3.3. Ozone Disinfection and Organic Matter Oxidation

On the other hand, it has been reported that permeability of the outer membrane, which is the main shelter of the cell against oxidant species, increases at alkaline pH values [16]. It could be expected that at pH 9.0 the cells turned more sensitive than at pH 7.0. This behavior was observed from the experiments and was rationalized by the ionization grade of sugars on the lipopolysaccharide (LPS) of the bacteria. LPS is considered the main component in the outer membrane of *E. coli* and it is known that this molecule has a net charge of −1.5 at neutral pH, when pH decreases, this net charge turns the cell membrane into a less hydrophilic conformation less permeable to polar species including the oxidant species at pH 9.0 [19].

Bacterial inactivation and COD removal from wastewater as function of the ozone dose (in mg/min) is presented in Figure 4. The higher the ozone dose, the higher the bacterial removal and COD oxidation. Best results were obtained with ozone doses about 20 mg/min where 72% and 78% of FC and TC, respectively were inactivated. No effect of pH was determined for fecal and total coliforms inactivation at the different pH values tested (pH = 5, 7 and 9, data not shown). This behavior, however, is reasonable if considering that molecular ozone is actually the chemical species carrying out bacteria disinfection instead of hydroxyl radicals, which will be affected by pH [20].

Ozone was also capable of oxidizing organic matter in the effluent measured as COD. The highest removal obtained was 36% for 20 mg/min of ozone. It is well known [21] that ozone reacts with organic matter, particularly with compounds including double bonds and/or aromatic structure in their chemical frame.

3.4. Estimation of Scaling-up Parameters

Despite many disinfection processes have been developed up to full-scale commercialization, frequently this scaling-up is carried out using heuristic approaches which not always consider important parameters such as the concentration of the contaminant or treatment goals.

To provide a set of comparative scaling-up parameters for the disinfection technologies proposed in this work, a figure-of-merit proposed by the Photochemistry Commission of the International Union of Pure and Applied Chemistry (IUPAC) was used [22]. This figure-of-merit is the electric energy per order (E_{EO}) defined as the electric energy (kW-h) required to degrade a contaminant by one order of magnitude in a unit volume of contaminated water. E_{EO} (kWh/m^3/order) in flow through operation is calculated by means of Equation (1) [23]:

$$E_{EO} = \frac{P}{F \log\left(c_i / c_f\right)} \tag{1}$$

where: *P* is the rated power (kWh) of the disinfection

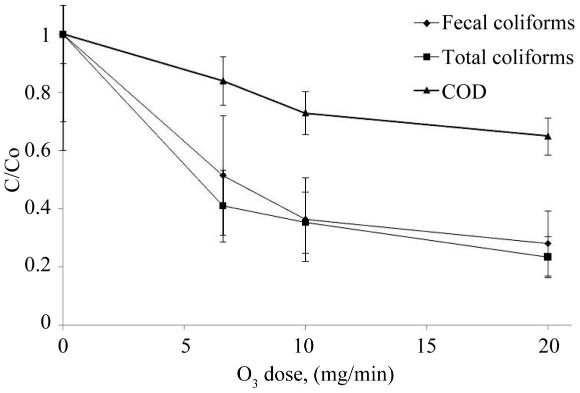

Figure 4. Total and fecal coliforms inactivation and COD removal with ozone.

system, F is the water flow rate (m^3/h) and c_i, c_f are the initial and final amount of microorganisms (CFU/mL).

Considering Equation (1), E_{EO} values for the different experimental conditions tested in this work were determined and are shown in **Table 2**. In all cases, fecal coliforms required the highest value of electric energy per order.

It is clear that E_{EO} values for the UV process are lower than those determined for the ozone process in all the water flows tested. As explained earlier, E_{EO} may represent the actual operational cost for every technology if energy cost is considered. This means that the lowest the E_{EO} value, the lowest the operational cost will be.

For both, UV and O_3 disinfection processes, the E_{EO} value was related to the water flow. For all cases, the higher the water flow, the lower the E_{EO} value. Thus, for UV disinfection, E_{EO} went from 447.5 kWh/m^3/order at 0.16 L/sec of water flow to 247.7 kWh/m^3/order when the water flow value was increased to 0.5 L/sec. However, this difference in the E_{EO} value is not proportional to the increase in the water flow: whereas water flow increased over 3 times, E_{EO} was reduced only about 1.8 fold. This trend could be due to the reaction kinetics involved in the disinfection process. Usually, disinfection kinetics is proposed to be accurately described by the Chick-Watson equation. In the case of radiation driven processes, Bandala *et al*., (2009) [24] have proposed the use of a modified Chick-Watson kinetics where the concentration of the disinfecting reagent is replaced by the energy dose.

They have found that the proposed mathematical approach fits the experimental values fairly well. In the case of the experiments described here, the presence of organic matter in the wastewater may lead to differences in the reaction kinetics which may produce non-linear relationships. The other possibility may be that the suspended solids may act as a "protective shell" for the microorganisms during the disinfection procedure and this may interfere with the proposed linear disinfection kinetics.

A similar trend was found in the case of the ozone disinfection process. In this case, the E_{EO} value decreased about 1.5 times (from 2529.7 to 1638 kWh/m^3/order) when the water flow was changed from 0.16 to 0.5 L/sec, a lower decrease than the one found in UV disinfection. The difference may be explained by the fact that ozone is able to react with organic matter present in the wastewater as observed in **Figure 3**. It is clear that this side reaction will generate changes in the disinfection kinetics even at a higher level than that described for the UV process.

Table 2. Electric energy per order (E_{EO}) values, in kWh/m^3/order, for the tested disinfection procedures as function of the water flow and microorganism type.

Tested	Microorganism	Water flow, L/sec		
		0.16	0.32	0.5
UV	Fecal coliforms	447.5	299.3	247.7
	Total coliforms	439.6	285.1	224.6
O_3	Fecal coliforms	2529.7	1654.6	1638.0
	Total coliforms	2327.6	1452.0	1248.2

4. Conclusions

UV radiation and ozonation were investigated as disinfection alternatives for the wastewater treatment plant at the Autonomous Metropolitan University—Azcapotzalco campus, evaluating the inactivation of total and fecal coliforms.

UV light presented a high bacterial inactivation, over 80%, while fecal coliforms were less affected by the increase in energy fluency than total coliforms.

Total coliforms showed higher inactivation rates than fecal coliforms at all the pH values tested but the lowest bacterial inactivation was observed at about pH 7.

Ozone displayed a low oxidation potential, and the best results were obtained for ozone doses of about 20 mg/min with removals of 72% and 78% of fecal and total coliforms, respectively. The maximum bacterial resistance was observed at pH values near 7, in both cases.

Ozone also led to a reduction of organic matter in the effluent measured as COD, the highest removal obtained being 36% for 20 mg O_3/min. Finally the E_{EO} (kWh/m^3/order) was obtained, being noteworthy that E_{EO} values for the UV process were lower than those determined for the ozone process in all the water flows tested.

For both UV and O_3 disinfection processes, the E_{EO} value was related to water flow (in all the cases, the higher the water flow is, the lower the E_{EO} value will be).

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