Pergamon

Wat. Sci. Tech. Vol. 40, No. 4–5, pp. 235–245, 1999
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0273–1223/99 $20.00 + 0.00

PII: S0273-1223(99)00505-3

ADVANCED TREATMENT AND DISINFECTION FOR MUNICIPAL WASTEWATER REUSE IN AGRICULTURE

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ABSTRACT

In a 3-year joint research project, approved in 1995 by the European Commission, methods for advanced treatment and disinfection of municipal wastewater to permit reuse in agriculture were investigated. Pathogen inactivation, disinfection by-products (DBP) formation and the cost effectiveness of disinfection methods involving UV rays, ozone (O_3) and peracetic acid (PAA) were evaluated. The investigation was carried out on municipal effluents which had received different degrees of treatment (secondary, clarified, clarified-filtered) in a 100 m^3/h pilot plant that was designed, built and operated at West Bari (S. Italy) municipal wastewater treatment plant. Under the experimental conditions investigated, the WHO microbial guideline for unrestricted reuse of wastewater in agriculture (1,000 CFU/100ml for Faecal Coliforms) was easily achieved with all three disinfectants, while the corresponding Italian standard (2 CFU/100ml) was effectively met only with UV at an O&M cost in the range 17.5-35 EURO/1000m^3. Log-inactivation values ≥ 5 for both UV and PAA and ≥ 3 for O_3 were obtained; selected pathogens were affected by UV and, in part, by O_3. No DBPs were detected with UV and PAA, while limited formation of aldehydes was found with O_3. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Disinfection; municipal effluent; peracetic acid; ozone; UV rays; wastewater reuse.

INTRODUCTION

Following the discovery that chlorine may produce harmful disinfection by-products (DBP), alternative disinfectants are being considered worldwide for meeting the sanitary standards required for wastewater discharge and reuse (WEF, 1996; IWSA, 1997). With this objective, a 3-year (1995-1998) project linking research teams from Israel, Malta, Morocco, Spain, UK and Italy as the leading country, supported in part by the Commission of the European Community, has been carried out on various technical and health care aspects of wastewater treatment for agriculture reuse. The research programme of the foreign partners of the project was centered on advanced disinfection with hydrogen peroxide and oligo-metals (Israel), identification and health-effects of chlorinated DBP (UK), biological impact on marine environment (Malta), low-cost treatment technologies (Spain) and agronomic effects (Morocco).

The Italian team was involved in pilot and laboratory investigation of advanced disinfection methods based on ultraviolet light (UV), peracetic acid (PAA) and ozone (O_3). Major engineering and sanitary aspects of the study concerned: technical efficiency in terms of pathogen inactivation, DBP formation and costs; hydrodynamics of UV disinfection; potential migration of selected DBP in soils, crops and the marine environment (in collaboration with Malta); epidemiology of waterborne diseases originating from municipal wastewater.

This paper summarizes the main experimental results, discussed in detail elsewhere (Liberti *et al.*, 1996, 1998, in press), of UV, PAA and O_3 disinfection achieved with a 100 m^3/h pilot plant. The latter, designed for investigating these 3 disinfectants and also equipped with multilayer filtration, has been built and operated at West Bari (Southern Italy) municipal wastewater treatment plant. Two effluents could be drawn from the plant before chlorination: one following secondary sedimentation, the other submitted also to post-precipitation with aluminum polychloride. Accordingly 3 feeds, namely *secondary* (II), *clarified* (CL) and *clarified-filtered* (F), have been alternatively treated with the 3 disinfectants in the pilot plant.

Specific objectives of this investigation were to assess:

- the effectiveness of disinfection using UV, PAA and O_3 with each feed by reference to the Italian microbial standard (2 CFU/100ml of Total Coliforms, based on the well-known 1978 California Wastewater Reclamation Criteria) as well as to 1989 WHO guideline (1,000 CFU/100ml of Faecal Coliforms) for unrestricted wastewater reuse in agriculture, paying special attention also to selected parasites and pathogens (Helminth eggs, *Giardia lamblia* cysts, *Cryptosporidium parvum* oocysts, *Pseudomonas aeruginosa*);
- the formation of disinfection by-products;
- the compliance of treated wastewater characteristics with agronomic regulations;
- disinfection costs.

UV, PAA AND O_3 MAIN FEATURES

It is well known that **UV** radiation in the range 240 to 280 nm wavelength range induces photochemical damage to RNA and DNA within the microbial cell, so that the organisms can no longer reproduce. At normal operating doses (20-200 mWs/cm^2), it is claimed that UV systems, either *submerged* or *unsubmerged* according to the water-lamp contact configuration, show biocidal action towards a wide variety of viable species with very fast kinetics and a lack of toxic DBP formation. In addition, they have relatively simple technology, of reasonable cost, and with no need for handling, storage and disposal of hazardous chemicals. The major drawbacks are: the absence of a bacteriostatic effect; the possibility of water recontamination by cell repair and photoreactivation; the unfavourable influence of water characteristics such as turbidity, suspended solids, colour, colloidal matter and dissolved organics causing shelter, scattering and absorption effects; the decline of UV output intensity due to lamp scaling and age (US-EPA, 1992; WERF, 1995).

Peracetic acid (CH_3COOOH) is a powerful antimicrobial agent recently proposed also for disinfecting drinking water, wastewater and even for municipal wastewater reuse. It is an unstable organic peracid commercialized as quaternary equilibrium mixture of acetic acid (CH_3COOH), hydrogen peroxide (H_2O_2), peracetic acid and water. It is reportedly not mutagenic or carcinogenic, and its disinfectant activity, increasing in acidic conditions where the undissociated acid prevails, is based on the release of active oxygen. At doses commonly adopted for wastewater discharge (1-5 ppm with $\leq$ 30 min contact time), PAA decomposes to harmless residuals such as acetic acid, oxygen and water, thus apparently not yielding harmful DBP. Major drawbacks associated with PAA disinfection are the increase of organic content in the treated effluents, the potential microbial regrowth due to the remaining acetic acid, the limited efficiency against viruses and parasites and the strong dependence on wastewater quality (Baldry and Fraser, 1988; Lefevre *et al.*, 1992)

Ozone is a strong disinfectant with high oxidation potential, potentially toxic and explosive requiring *on-site* generation. At doses usually reported for wastewater discharge (5-10 ppm with 5-15 min contact time) O_3 may form relatively harmful DBP (e.g., bromates) being also capable of oxidizing organic DBP precursors. Key factors affecting ozone disinfection are mass transfer efficiency, mixing, contact time and minimal short–circuiting as pursued with different ozonation systems (e.g., *diffused bubble, negative pressure or Venturi*), while it is negatively affected by soluble or suspended matter (Langlais *et al.*, 1991; Masschelein, 1991).

MATERIALS AND METHODS

West Bari municipal wastewater treatment plant treats the sewage of approx. 300,000 inhabitants (3,000 m^3/h) by primary (mechanical screening and sedimentation, including pre-precipitation with $pAlCl_3$) and secondary treatments (activated sludge with biological denitrification followed by sedimentation). A fraction of the secondary effluent (approx. 600 m^3/h) undergoes also post-precipitation (i.e., coagulation and flocculation with 30-40 mg/l of $pAlCl_3$, followed by 6 hrs sedimentation at hydraulic linear velocity of 0.9 m/hr). Final disinfection occurs by chlorination.

The pilot plant, shown in Figure 1, permits a comparison of the performance of the various disinfectants (UV, PAA, O_3) with feeds of increasing quality. Unchlorinated *secondary* (II) and *clarified* (CL) feeds were drawn directly from the West Bari plant. The *clarified-filtered* feed (F) was obtained by filtering CL on a multilayer pressure filter (MF) filled with high purity silica sand and gravel. The 5 m^3 fibre-glass vessel (RV) was used for batch disinfection with the PAA mixture *Oxymaster* (PAA 15.5 %, H_2O_2 22.8 %, Acetic acid 17 %), kindly provided by Solvay Interox (Livorno, I). UV disinfection occurred in a non-contact UV apparatus (UVA, mod. 600 L Super, maximum flow rate 140 m^3/h, kindly provided by UVT, Taranto, I), in which the water flow is split between 15 parallel, inverted, U-shaped Teflon tubes. These were surrounded externally by 62 low pressure (0.2 atm) Hg vapor lamps. Disinfection with O_3 was carried out with an industrial system (mod. NFW 410, maximum production rate 445 gO_3/h), kindly provided by Cillichemie (Milan, I) where O_3 was added to the feed through the ejector (O3E) and the hydrokinetic mixer (O3M). The feed then entered the reaction tower (O3T) consisting of a 5 m^3 fibre-glass vertical closed tank. Ozone was generated from air by high tension (max. 15 kV) electric discharge in the production unit (O3P). Wastewater samples were collected from sampling ports 1 to 7.

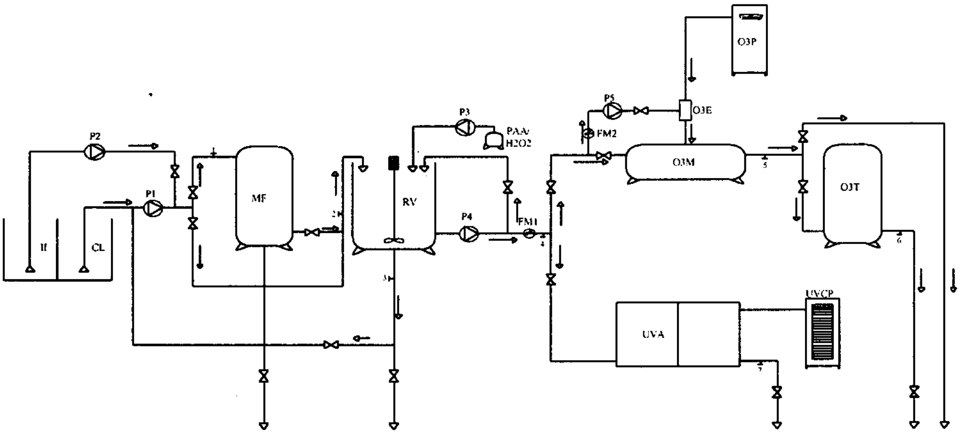

Figure 1. Flow-sheet of West Bari 100m^3/h pilot plant.

Under the experimental conditions used, maximum UV dose (D) amounted to 430 mWs/cm^2, calculated as $D = I \times t$, where I (average UV intensity inside the Teflon tubes) was 12.2, 9.9 and 8.8 mW/cm^2 for F, CL and II feeds respectively and t (exposure time in UV reactor, i.e., hydraulic retention time) was ≤ 50 sec. Similarly, maximum available dosages amounted to 15 ppm of applied O_3 (transferred only in part to the feed) with contact time ≤ 15 min and to 500 ppm PAA with contact time ≤ 60 min respectively.

For each disinfectant, first the best feed (i.e., clarified-filtered, F) was submitted to increasing doses until the target count of Total Coliforms was achieved (if possible). When the target count was achieved, the poorer feeds (i.e., clarified, CL and secondary, II, in that order) were then treated similarly. In particular, during PAA cycles, 3 m^3 of each feed were added batchwise in RV with the appropriate PAA dosage and mixed for different contact times. During UV cycles, 5 m^3 were conveyed to the UV apparatus at the given flow rate and exposed to the corresponding UV dose. During O_3 cycles, 5 m^3 were treated with the given O_3 dosage through the ejector (O3E), mixed through the hydrokinetic mixer (O3M) and then held batchwise in the reaction tower (O3T) for the given contact times. For the sake of reproducibility, each run was done in triplicate so that each cycle (i.e., one feed submitted to a given dose of the given disinfectant for a given contact time) lasted approx. one full working day. Between July 1996 and January 1998, a total of 88, 76 and 68 cycles were carried out for UV, PAA and O_3 respectively, according to the planned schedule, using the appropriate configuration of the pilot plant.

Feed characteristics were analysed routinely including Temperature, pH, Conductivity, Alkalinity, Total Suspended Solids, Total Dissolved Organic Carbon, Turbidity, Transmittance at 254 nm, NH_4^+, $N\text{-}NO_3^-$, $N\text{-}NO_2^-$ and Total Coliforms (before and after disinfection). Once the microbial standard was achieved, three more cycles were conducted with the same conditions in order to assess those parameters of agronomic interest in the disinfected effluent (pH, TSS, Sodium Adsorption Ratio, BOD_5, COD). In addition, selected parasites and pathogens (Helminths, *Giardia lamblia* cysts, *Cryptosporidium parvum* oocysts and *Pseudomonas aeruginosa*) were monitored before and after disinfection. Finally, the eventual formation of DBP (i.e., nitro-phenols and N-nitroso-amines for UV, total epoxides and 2/4/2,4 chloro-phenols for PAA, total aldehydes, bromates and bromoform for O_3) was investigated. Collection, storage and analytical procedures were done according to *Standard Methods*, unless specified differently (Liberti *et al.*, 1998).

SUMMARY OF RESULTS AND DISCUSSION

Table 1 reports the main characteristics of the three feeds throughout the investigation period, clearly showing the differences in quality for II, CL and F effluents, in particular for those parameters potentially affecting disinfection performance, i.e., TSS, Turbidity and Total Coliforms.

Table 1. Main characteristics of secondary (II), clarified (CL) and clarified-filtered (F) feeds

	II			**CL**			**F**		
	ave	**Min**	**max**	**ave**	**min**	**max**	**ave**	**min**	**max**
Temperature(°C)	19	17	20	21	16	27	20	16	25
pH	7.6	7.5	7.7	7.6	6.7	8.6	7.6	6.8	8.0
Conductivity (mS/cm)	1842	1560	4390	2100	1271	6300	2040	1330	6330
Turbidity (NTU)	9	5.1	29.3	5	2.3	10.4	2.1	1.2	4.0
TSS (mg/l)	20	11	39	13	6	27	5	3	10
DOC (mg/l)	13	5	28	10	3	24	10	5	24
254 nm Transmittance (%)	56	44	63	61	55	66	67	60	70
NH4 (mg/l)	28.1	21	43.4	24.5	11.5	35.5	26.3	13.8	50.5
N-NO3 (mg/l)	1.32	0.36	3.58	0.33	0.01	1.59	0.69	0.01	3.13
N-NO2 (mg/l)	0.39	0.08	0.72	0.39	0.01	1.24	0.32	0.01	1.24
Total Coliforms 1000 (CFU/100ml)	1710	8	6370	983	0.43	4550	387	0.2	1600

Disinfection effectiveness

The effectiveness of disinfection for Total Coliforms has been evaluated for each disinfectant and each feed according to the operating procedures previously described. Table 2 and Figure 2 summarize the most relevant results obtained. These data indicate that, under the experimental conditions investigated, the Italian target standard for unrestricted reuse of municipal wastewater in agriculture (2 CFU/100ml of Total Coliforms) was achieved only with clarified-filtered or clarified feeds disinfected with 100 and 160 mWs/cm^2 UV dose respectively. This is in agreement with similar investigations (Snider *et al.*, 1991; Awad *et al.*, 1993). However, the less stringent WHO guideline (1,000 CFU/100ml of Faecal Coliforms) was always achieved with all disinfectants and feeds used.

It is worth noting, as expected, the extremely fast kinetics of UV *physical* disinfection (contact time ≤ 30 sec) compared with O_3 or PAA *chemical* disinfection (≥ 5 min). Log-inactivation values ≥ 5 were obtained with UV and PAA, compared with ≤ 4 with O_3, although this parameter may be unreliable when the colimetric content of the feed is highly variable, as in the present case.

Table 2. Summary of disinfection effectiveness of UV, PAA and O_3 towards Total Coliforms

Feed	period of Investigation	Disinfectant	Dose	no. of cycles	No			N			log (No/N)		
					ave	min	max	ave	min	max	ave	min	max
F	July-Oct 96	UV	100 mWs/cm^2	9	120	0.2	460	1	0	2	4.7	2.2	6.0
	March-June 97	PAA	400 ppm, 20 min	5	362	120	625	2	1	2	5.2	5.0	5.5
			10 ppm, 30 min	14	438	70	900	240	10	680	3.4	2.3	4.6
	Nov97-Jan98	O3	15 ppm, 10 min	8	800	270	1600	97	60	160	3.9	3.5	4.4
CL	Dec96-Jan97	UV	160 mWs/cm^2	8	694	100	2000	1	1	2	5.7	5.0	6.0
	Sept97-Jan98	O3	15 ppm, 10 min	15	1400	300	4550	1060	275	2350	3.1	2.3	3.5
II	Dec96-Feb97	UV	430 mWs/cm^2	11	908	210	3700	5	1	19	5.3	4.9	6.0

No: Total Coliforms content before disinfection (1000 CFU/100ml)
N: Total Coliforms content after disinfection (CFU/100ml)
II: secondary, CL: clarified, F: clarified-filtered feeds

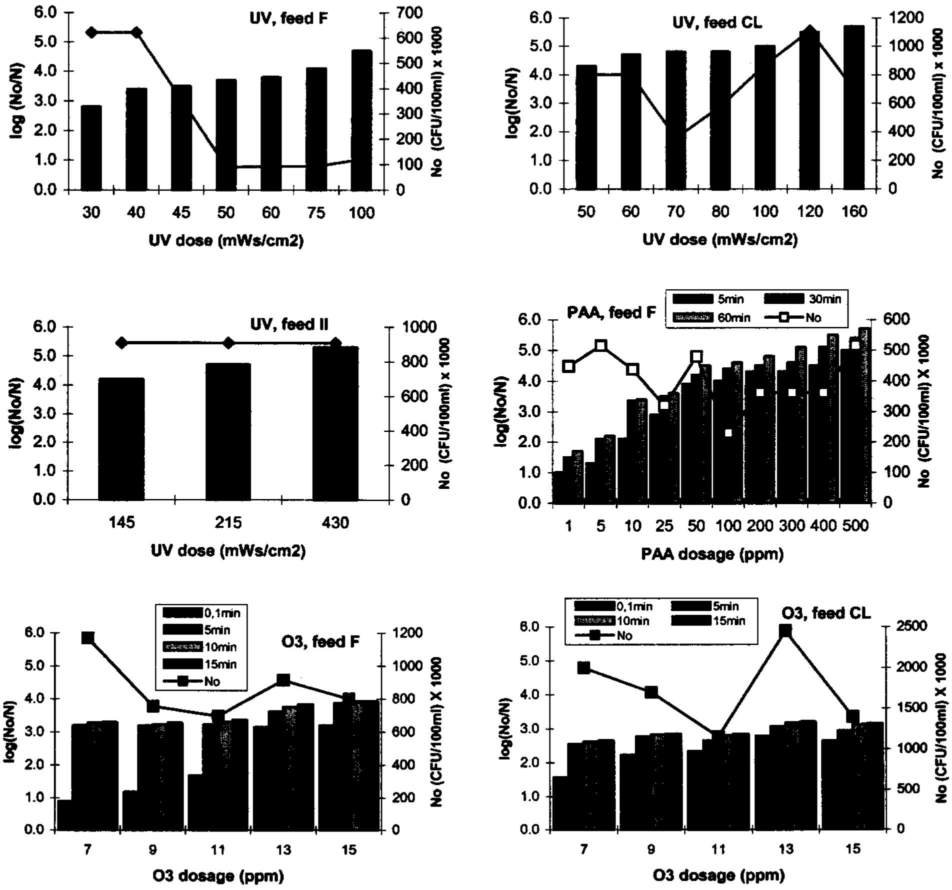

Figure 2. Total Coliforms log-inactivation with UV, PAA and O_3

Although small doses (1-5 ppm) of PAA and O_3 have been reported to be sufficient to reach the Total Coliform standard of 2 CFU/100ml during disinfection of drinking water, the same result is not achievable with municipal effluent since both powerful oxidants are rapidly consumed by organic and other oxidizable impurities. In fact, this target has been achieved with such low O_3 doses only when wastewater is previously submitted to clarification, sand-filtration and activated carbon adsorption (US-EPA, 1986). In the present investigation, the target was also achieved with PAA on the clarified-filtered feed only, using very high dosages (400-500 ppm) with a contact time of 20 min, i.e., under economically prohibitive conditions, in agreement with Mandra *et al.* (1996).

Major limiting factors for disinfection performance in the present investigation were confirmed to be O_3 gas transfer to the liquid phase and effective PAA mixing with wastewater (US-EPA, 1986). Similarly, TSS and/or Turbidity (not DOC content) were the limiting parameters for UV disinfection, reducing UV transmittance in the treated wastewater by a scattering effect (Snider *et al.*, 1991).

Effect on selected pathogens

In this study, the effectiveness of the chosen disinfectants towards selected pathogens commonly occurring in local municipal wastewater was also evaluated and the results are shown in Table 3. As indicated, Helminth eggs were never found in the feeds before disinfection, confirming that heavy and large parasites are consistently retained by clarification and filtration treatments. The data in Table 3 also indicate that all disinfectants were effective towards bacteria like *Pseudomonas aeruginosa*. Parasites like *Giardia lamblia* cysts and *Cryptosporidium parvum* oocysts were both affected by UV, O_3 was rather effective towards *Giardia* only while PAA was basically ineffective towards both parasites. These results agree only in part with previous data on O_3, reportedly effective also towards *Cryptosporidium* (Langlais *et al.*, 1991). Better agreement was found instead with PAA efficiency towards pathogens which can be ranked thus: *bacteria>viruses>bacterial spores>protozoan cysts* (Rudd and Hopkinson, 1989), as well as with UV, for which 60 to 180 mWs/cm^2 doses are claimed to yield 80 to 99% reduction of *Giardia* and *Cryptosporidium* (Campbell *et al.*, 1995). However, due to the low precision of microbiological measurements at low parasite concentration, the above conclusions should be considered speculative.

This project confirmed that the *multiple barrier concept* (i.e., filtration plus disinfection) offers the most effective approach for complete parasite removal in water and wastewater treatment (Karanis *et al.*, 1992).

Table 3. UV, PAA and O_3 disinfection effectiveness towards selected pathogens

		UV		**PAA**		**O3**	
		100 or 160 mWs/cm^2 *		10 ppm, 30 min		15 ppm, 10 min	
Pathogen	**Feed**	**In**	**Out**	**In**	**Out**	**In**	**Out**
Helminths (N/l)	F	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
	CL	0/0/0	0/0/0			0/0/0	0/0/0
Giardia lamblia (N/l)	F	80/110/150	20/60/50	20/18/12	19/17/12	41/13/46	7/10/14
	CL	411/347/278	124/188/156			125/123/390	2/37/237
Cryptosporidium parvum (N/l)	F	40/2/1	15/1/1	1/2/1	1/2/1	1/1/3	1/1/3
	CL	7/21/7	0/6/3			1/5/24	0/5/14
Pseudomonas Aeruginosa (CFU/100ml)	F	8/2×10^5/0	3/2/0	12,500/10,000/ 1,200	9/0/20	300/2,500/1,600	12/4/8
	CL	3.6×10^6/9,600/ 4.8×10^5	1/0/0			1,900/1,000/400	10/60/14

* treating feed F or CL respectively

DBP formation

It cannot be excluded, in principle, that UV irradiation of wastewater may affect the identity of the organic substances through either *direct* or *indirect* interaction and form potentially toxic by-products (von Sonntag and Schuchmann, 1992). In the former case, a molecule known as a *chromophore* may be chemically modified as a result of a direct radiation absorption. Indirect photolysis may occur when UV radiation acts on a species known as a *photosensitiser* which strongly absorbs the radiation energy and the resulting highly energetic species interacts with another molecule producing a chemical transformation. Since amino- and phenolic-derivatives (chromophores) as well as nitrate/nitrite ions and humic materials (photosensitisers) are commonly found in municipal wastewater, during the present investigation N-nitroso-amines and nitro-phenols were specifically targeted as possible DBP following UV disinfection. As summarized in Table 4, however, none of these N-derivatives was ever detected, even at the highest UV doses. It may be concluded that, under the conditions investigated, no chemical transformation occurs during UV disinfection of municipal wastewater, as found in other similar investigations (Elsinore Valley, 1994; Linden *et al.*, 1998).

Table 4. DBP formation after UV, PAA and O_3 disinfection of CL and F feeds

			DBP							
Disinfectant	**Dose**	**feed**	In	Out	In	Out	In	Out	In	Out
UV			**Nitro-phenols (ppb)**		**N-nitroso-amines (ppb)**					
	100 mWs/cm^2	**F**	N.D.	N.D.	N.D.	N.D.				
	160 mWs/cm^2	**CL**	N.D.	N.D.	N.D.	N.D.				
PAA			**Total Epoxides ^**		**2/4/2,4 Chloro-phenol (ppb)**					
	10 ppm, 30 min	**F**	N.D.	N.D.	N.D.	N.D.				
O3			**Total Aldehydes ***		**Bromides** (ppm)		**Bromates (ppm)**		**Bromoform (ppb)**	
	15 ppm, 10 min	**F**	0.12	0.47	4.13	4.21	N.D.	N.D.	0.48	0.54
	15 ppm, 10 min	**CL**	0.11	0.45	3.48	3.32	N.D.	N.D.	0.31	0.32

^ expressed as hydrogen peroxide (ppb); * expressed as formaldehyde (mg/l); In/Out: before/after disinfection

Even though PAA is considered to decompose to oxygen, water and acetic acid, the possibility that it could form harmful DBP cannot be completely ignored. About 10-30 ppb of aldehydes have been reported to form as transformation and/or oxidation DBP when PAA interacts with amino acids, phenols and other aromatic substances present in treated sewage (Crathorne *et al.*, 1991). Aldehydes are thought to be hepato-toxins at high dosages (ppm levels), but no toxic effects are expected at ppb concentration level. During the present investigation, indeed, about 120 ppb of aldehydes were already present in the feeds before PAA disinfection, hence their eventual further formation was ignored. Another possibility was the formation of brominated haloforms due to the presence of 3-4 ppm of bromide ion in the feeds investigated (Booth and Lester, 1995). The co-occurrence of 20-25 ppm of NH_4^+ ion, however, also prevented this possibility because the reaction rate between NH_3 and HOBr was found to be much greater ($k=8\times10^7$ M^{-1} s^{-1}) than between HOBr and organic matter ($k=20$ M^{-1} s^{-1}). It is most likely that, in the present situation, epoxides and halogenated organic compounds such as chlorinated phenols could be formed (Rudd and Hopkinson, 1989). Therefore, epoxides (as sum parameter) and chlorinated phenols (as 2-Chlorophenol, 4-Chlorophenol and 2,4 Dichlorophenol) were investigated following PAA disinfection. Table 4 demonstrates that, even for PAA, the expected formation of DBPs did not occur under the experimental conditions investigated. Indeed, epoxides are very unstable and, if formed, should behave as reaction-intermediates that immediately decompose to H_2O_2 and carbonyl-containing products. Chlorinated phenols are reported to form only under very severe conditions (Booth, 1995), not occurring in the present investigation.

The reaction mechanism of O_3 with organics involves the direct reaction of O_3 molecule or the intervention of less selective but much more reactive radical species. Both molecular and free radical ozone pathways resulting from its complex decomposition, as well as the nature of organic matter which serves as precursor material, play a role in the possible formation of harmful DBP during ozone disinfection (Minear and Amy, 1996). A number of studies, particularly in the field of drinking water treatment, have identified several ozone DBPs like mono- and dicarboxylic acids, mono- and diketones, alkanes, phthalates, organic peroxides, epoxides and aldehydes. In the last group, only simpler aldehydes (i.e., formaldehyde, acetaldehyde, glyoxal, propanal, butanal, pentanal and acetone) are likely to form in appreciable amounts (ppb level) under common disinfection conditions (Schechter and Singer, 1995). In 1995, the European Commission included bromates and brominated THMs, potentially formed during the ozonation of Br^- containing waters, in the list of potentially toxic DBP. Accordingly, the formation of bromate (BrO_3^-), bromoform ($CHBr_3$) and aldehydes (measured as sum parameter) was assessed after O_3 disinfection during the present investigation. Only the last of these was found to form in appreciable amounts (about 350 ppb, see Table 4) during ozonation. No bromates were found probably due to the basic pH (7.6) of the feed, while bromoform, already present in the feed, showed a negligible increase in concentration, perhaps as a consequence of the relatively high NH_4^+ content of the feed (von Gunten and Hoignè, 1992).

Compliance with agronomic regulations

According to Italian regulations, apart from Total Coliforms, other parameters of agronomic interest (pH, TSS, BOD_5, COD, Sodium Adsorption Ratio and Boron) should comply for reuse of municipal wastewater in agriculture. As shown in Table 5, compliance with such regulations was always achieved, regardless of the disinfectant and the type of feed used (CL or F) for all the considered parameters (except for Total Coliforms, for which the standard was only met after UV disinfection).

Table 5. Agronomic characteristics of CL and F effluents disinfected with UV, PAA and O_3

Parameter		**feed**	**UV effluent ^**	**PAA effluent ^**	**O_3 effluent ^**	**MAC°**
pH		F/CL	8.1/7.8	7.5	7.8/7.7	5.5-9.5
TSS	(mg/l)	F/CL	3/8	6	6/10	80
BOD5	(mg/l)	F/CL	10/5	12	4/5	40
COD	(mg/l)	F/CL	40/57	54	51/59	160
Boron	(mg/l)	F/CL	1.3/0.9	1.1	0.8/0.9	2
Sodium Adsorption Ratio		F/CL	6/6	7	7/7	15

^ **UV**: 100 or 160 mWs/cm^2 (treating feed F or CL respectively); **PAA**: 10 ppm, 30 min; **O_3**: 15 ppm, 10 min

° Maximum Allowable Concentration for agriculture reuse fixed by Italian Regulations (L.319/76, DCI 4/2/77)

Furthermore, it must be emphasized that the proven occurrence of some parasites in the disinfected effluents (see Table 3) does not restrict their reuse in agriculture. In fact, according to WHO, the only parasites of concern are the intestinal nematodes (MAC < 1 egg/l), which belong to the Helminths, a group never found during this investigation.

Cost estimates

The economic feasibility of using UV, PAA and O_3 for advanced disinfection can be evaluated on the basis of the experimental results obtained. Towards this aim, estimates were made with reference to the optimal dose of each disinfectant for each feed that permitted the achievement of the 2 CFU/100ml Total Coliform standard and/or the WHO 1,000 CFU/100ml Faecal Coliform guideline with the following assumptions:

- operation & maintenance (O&M) costs only are considered;
- UV doses of 100, 160 and 430 mWs/cm^2 for disinfecting feeds F, CL and II respectively; PAA dosages of 10 and 400 ppm for feed F; O_3 dosage of 15 ppm for disinfection of feeds F and CL are considered;
- major costs account for electricity consumption and lamp replacement (UV), for chemicals consumption (PAA), for electricity consumption and generator replacement (O_3) respectively;
- maintenance requirements and miscellaneous equipment repair costs for UV and O_3 are included in UV lamp and O_3 generator replacement costs respectively, while for PAA they are negligible;
- average electricity cost is 0.065 EURO/kWhr (1 EURO = 2,000 Italian Liras);
- electricity consumption of UV and O_3 equipment is 3.1 and 15.8 kWhr respectively;
- UV lamp (45 EURO/each) and O_3 generator (400 EURO/each) replacement is based on 8,760 and 26,280 hours of use respectively;
- PAA-based Oxymaster, including the transport, costs approx. 1 EURO/kg.

A summary of the cost analysis is reported in Table 6. As indicated, the stringent 2 CFU/100 ml Total Coliform standard was steadily achieved with proper UV dose both on the clarified (CL) and the clarified-filtered (F) feed with an O&M cost of 35 and 17.5 EURO/1000m^3 respectively. The same target was achieved with PAA on feed F only, at the excessive cost of 2,580 EURO/1000m^3 and it was never attained with O_3 under the conditions investigated.

Table 6. Cost estimates for UV, PAA and O_3 disinfection of II, CL and F feeds at West Bari pilot plant

Disinfectant	**Dose**	**feed**	**Flowrate (m^3/h)**	**Total Coliform target achieved (CFU/100 ml)**	**O&M costs (EURO/1000m^3)**			
					Electric power	**replacement**	**chemicals**	**TOTAL**
UV	100 mWs/cm^2	F	30	1	6.7	10.6		**17.3**
	160 mWs/cm^2	CL	15	1	13.5	21.3		**34.8**
	430 mWs/cm^2	II	5	5	40.3	63.7		**104**
PAA	10ppm,30min	F	30	240			64.5	**64.5**
	400ppm, 20min	F	30	2			2,580	**2,580**
O3	15ppm,10min	F	30	97	34.2	3.1		**37.3**
	15ppm, 10min	CL	30	1060	34.2	3.1		**37.3**

The economic conclusions are quite different if the WHO microbial guideline is considered. The data in Table 6, indeed, show that all three disinfectants can be used to achieve this aim, at proper doses, with tertiary feed (F) and the O&M cost increase, contrary to the performance achieved, follows the order $UV < O_3 < PAA$. To use O_3 to disinfect CL feed cost 37.5 EURO/1000m^3 and this substantially reached the WHO target. The cost effectiveness of UV disinfection is further confirmed by the possibility of meeting the WHO target even with the poorest quality feed (II) at a cost which is still affordable.

It should be noted, however, that the above estimates do not include capital costs (almost negligible for PAA disinfection) and can be influenced by a wide range of variables, such as feed quality, plant configuration, plant size (scale factor) and market situation.

CONCLUSIONS

The pilot (100 m^3/h) investigation carried out at West Bari (Southern Italy) municipal wastewater treatment plant between June 1996 and January 1998 permitted a comparison of the performances of three alternatives (UV rays, Peracetic Acid and Ozone) to chlorination as a method of disinfection of municipal wastewater for reuse in agriculture. On the basis of the results obtained by treating wastewater of varying strengths, namely *secondary* (II), *clarified* (CL) and *clarified-filtered* (F), with different experimental conditions, the following conclusions can be summarised:

- a clarification-filtration tertiary treatment stage was required to obtain a municipal effluent of consistently high quality to be effectively disinfected, according to Italian agronomic regulations;
- the stringent microbial standard for unrestricted reuse of municipal wastewater in agriculture (2 CFU/100ml for Total Coliforms), requiring log-inactivation value ≥ 5, was achieved with UV disinfection of either CL or F feeds with a dose of 160 and 100 mWs/cm^2 respectively. Similar results required very high doses (400 ppm and 20 min) of peracetic acid on F feed only and were never achieved with ozone;
- the corresponding WHO guideline (1,000 CFU/100ml for Faecal Coliforms) was easily achieved with all three disinfectants on feeds CL and F;
- all three disinfectants were very effective against bacteria like *Pseudomonas aeruginosa*. Parasites like *Giardia lamblia* cysts and *Cryptosporidium parvum* oocysts were affected by UV radiation, while O_3 was rather effective only towards *Giardia* and PAA showed poor action towards such resistant pathogens;
- harmful disinfection by-products were not found to form after UV or PAA disinfection, while limited formation of aldehydes occurred during O_3 disinfection;
- O&M costs ranged from 17.5 up to 2,600 EURO/1000m^3 for UV and PAA disinfection respectively (2 CFU/100ml for Total Coliforms) and 37.5 EURO/1000m^3 for O_3 (1,000 CFU/100ml for Fecal Coliforms).

Further investigations are planned on the following major aspects:

- application of the alternative disinfection methods to full tertiary municipal wastewater;
- possible synergy and/or catalytic effects of mixed disinfectants;
- more extensive search for possible DBP formation;
- full scale cost evaluation of the whole process (advanced wastewater treatment and disinfection).

ACKNOWLEDGEMENTS

This work was partly supported by the European Commission under the Avicenne 1994 Initiative with the contract No. AVI-CT94-0010 "Advanced disinfection and health-care aspects of wastewater reclamation and reuse in agriculture in Mediterranean regions".

REFERENCES

Awad J., Gerba C. and Magnuson G. (1993). Ultraviolet disinfection for water reuse. In: *Proc. of WEF Specialty Conference Series: Planning, Design and Operation of Effluent Disinfection Systems,* Water Environ. Fed. (ed.), Alexandria, pp. 1-12.

Baldry M.G.C. and Fraser J.A.L. (1988). Disinfection with peroxygens. In: *Critical Reports on Applied Chemistry,* K.R. Payne (ed.), vol. 23, John Wiley & Sons, Chichester, pp. 91-116.

Booth R.A. and Lester J.N. (1995). The potential formation of halogenated by-products during peracetic acid treatment of final sewage effluent. *Wat. Res.,* **29**(7), 1793-1801.

Campbell A.T., Robertson L.J., Snowball M.R. and Smith H.V. (1995). Inactivation of oocysts of Cryptosporidium Parvum by ultraviolet irradiation. *Wat. Res.,* **29**(11), 2583-2586.

Crathorne B., Fawell J., Irving T., Harris N., Denny S., Whitmore T., Horth H., Roddie B., Smith D.J. and Taylor L. (1991). *Sewage disinfection: by-product formation, ecotoxicology and microbiological efficacy,* Report NR 2727, Water Research Centre, Medmenham, UK.

Elsinore Valley Municipal Water District and National Water Research Institute (1994). *A comparative study of UV and chlorine disinfection for wastewater reclamation,* Executive Summary, Montgomery, Pasadena, USA.

IWSA (1997). *The practice of chlorination: application, efficacy, problems and alternatives.* International Water Supply Association Blue Pages, August 1997.

Karanis P., Maier W. and Seitz H. (1992). UV sensitivity of protozoan parasites. *J. Water SRT-Aqua,* **41**(2), 95-100.

Langlais B., Reckhow D. and Brink D. (1991). *Ozone in water treatment - Application and engineering.* Lewis publishers, Chelsea.

Lefevre F., Audic J.M. and Ferrand F. (1992). Peracetic acid disinfection of secondary effluents discharged off coastal seawater. *Wat. Sci. Tech.,* **25**(12), 155-164.

Liberti L., Notarnicola M., Zicari S., Carnimeo D., Arena R. and Portincasa F. (1996). Advanced disinfection for municipal wastewater reuse in agriculture: first results with UV treatment of clariflocculated and filtered secondary effluent. In: *Proc. of International Workshop on sewage treatment and reuse for small communities: mediterranean and european experience,* R.Choukr-Allah (ed.), Agadir, Morocco, pp. 425-436.

Liberti L., Lopez A. and Notarnicola M. (1998). UV disinfection of clarified secondary effluent for municipal wastewater reuse in agriculture. In: *Proc. of Disinfection '98 - WEF Specialty Conference,* Water Environ. Fed. (ed.), Alexandria, pp. 47-57.

Liberti L., Lopez A. and Notarnicola M. (in press). Disinfection with peracetic acid for municipal wastewater reuse in agriculture. *J. Instn. Wat. & Envir. Mangt.*

Linden K.G., Soriano G.S. and Darby J.L. (1998). Investigation of disinfection by-product formation following low and medium pressure UV irradiation of wastewater. In: *Proc. of Disinfection '98 - WEF Specialty Conference,* Water Environ. Fed. (ed.), Alexandria, pp. 137-147.

Mandra V., Lazarova V., Dumoutier N. and Audic J.M. (1996). Etude comparative de la desinfection des eaux residuaires urbaines par l'acide peracetique, l'irradiation UV et l'ozone. In: *Proc. of JIE96, Conf. du traitement des Eaux et des nuisances de poitiers.*

Masschelein W.J. (1991). *Ozone et ozonation des eaux.* IO_3A Comitè Europeen, Lavoisier-Tec&Doc, Paris.

Minear R.A. and Amy G.L. (1996). *Disinfection by-products in water treatment.* CRC Press, New York.

Rudd T. and Hopkinson L.M. (1989). Comparison of disinfection techniques for sewage and sewage effluents. *J. Instn. Wat. & Envir. Mangt.,* **3**, 612-618.

Schechter D. and Singer P. (1995). Formation of aldehydes during ozonation. *Ozone Sci. & Eng.,* **17**(1), 53-69.

Snider K.E., Darby J.L. and Tchobanoglous G. (1991). *Evaluation of ultraviolet disinfection for wastewater reuse applications in California,* Report of Dept. of Civil Engineering, University of California, Davis, USA.

US-EPA (1986). *Municipal wastewater disinfection-Design manual,* Report EPA/625/1-86/021, United States Environmental Protection Agency, Washington, USA.

US-EPA (1992). *Ultraviolet Disinfection Technology Assessment,* Report EPA 832-R-92-004, United States Environmental Protection Agency, Washington, USA.

von Gunten U. and Hoignè J. (1992). Factors controlling the formation of bromate ion during ozonation of bromide-containing waters. *J. Water SRT - Aqua,* **41**(5), 299-304.

von Sonntag C. and Schuchmann H.P. (1992). UV disinfection of drinking water and by-product formation - some basic considerations. *J. Water SRT - Aqua*, **41**(2), 67-74.

WEF (1996). *Disinfecting Wastewater for Discharge & Reuse. Proceedings of WEF Specialty Conference*, Water Environment Federation, Alexandria, USA.

WERF (1995). *Comparison of UV irradiation to Chlorination: guidance for achieving optimal UV performance,* Project Report 91-WWD-1, Water Environment Research Foundation, Alexandria, USA.