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Advanced Treatment For Municipal Wastewater Reuse In Agriculture. III - Ozone Disinfection

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Abstract

Results of a pilot (100 m^3/h) investigation on ozone disinfection of municipal tertiary effluents for reuse in agriculture carried out at West Bari (S. Italy) treatment plant are presented. Among dosages, contact times and advanced treatment schemes investigated it was demonstrated that ozone disinfection results in the achievement of the WHO microbial guideline (1,000 CFU/100ml for Fecal Coliforms) for unrestricted wastewater reuse in agriculture of both clarified and clarified-filtered municipal secondary effluents; it is very effective towards *Pseudomonas aeruginosa*, rather effective towards *Giardia lamblia* and substantially ineffective towards *Cryptosporidium parvum* and it forms limited amount of DBP (approx. 350 ppb of total aldehydes). O&M costs amount to 37 Euro/1000m^3.

Introduction

Although already integrated in many national water strategies (California, Arizona, Israel etc.) as rational resource management and alternative option for agriculture, wastewater reuse still brings along controversial viewpoints. Indeed, wastewater microbial (bacteria, viruses and parasites) and chemical (toxic and trace elements) composition strongly limits the reuse, imposing crop restrictions and constraints to users for the potential food chain transfer of pollutants via the wastewater-soil-plant-human route (Rowe and Abdel-Magid, 1995).

Various schemes of advanced (or tertiary) treatment have been proposed in the last two decades with the so called "full Title 22" scheme, i.e., secondary effluent further submitted to clarification/flocculation, sand filtration and final disinfection with chlorination (State of California, 1978) most commonly adopted. However, due to its operating cost, the tendency exists to avoid filtration in the above scheme whenever possible, particularly in the less developed areas such as North Africa and Middle East (Asano, 1998).

Furthermore, after the recognition (Rook, 1974) that chlorination may produce harmful disinfection by-products (DBP), reliable alternative disinfectants to chlorine and its compounds are being extensively searched for worldwide (WEF, 1996; IWSA, 1997).

Both objectives (i.e., simpler tertiary treatments and alternative disinfectants to chlorination) were pursued within a 3-year R&D project committed in 1995 by the Commission of the European Community, aimed at comparing O_3, UV, H_2O_2 and Peracetic Acid with chlorine for the disinfection of differently treated municipal effluents to be reused in agriculture. To this aim, a field investigation was carried out on a 100 m^3/h pilot plant purposely built at West Bari (S. Italy) municipal wastewater treatment facility, where 3 secondary effluents (untreated, clarified, clarified-filtered) were alternatively treated with the 4 disinfectants (Liberti et al., 1998, 1999a; Liberti and Notarnicola, 1999).

This paper reports on the ozone disinfection of clarified and clarified-filtered effluents. Specific targets of the investigation were:

- to evaluate O_3 disinfection effectiveness for meeting the well known Californian microbial standard (2 CFU/100ml for Total Coliforms, also adopted in Italy) and the WHO (1989) guideline (1,000 CFU/100ml for Fecal Coliforms) for unrestricted reuse of wastewater in agriculture;
- to assess the effect of ozonation towards selected pathogens often occurring in municipal wastewater (*Nematodes* eggs, *Giardia lambia* cysts, *Cryptosporidium parvum* oocysts, *Pseudomonas aeruginosa*);
- to search for eventual DBP formation;
- to comply with agronomic regulations;
- to draw preliminary economic estimates.

Ozone Disinfection

O_3 is an unstable gas produced by electric discharge in a gas phase (air or pure oxygen) when oxygen molecules are dissociated into atomic oxygen and subsequently collide with another oxygen molecule. It is a strong disinfectant with high oxidation power, potentially toxic and explosive, requiring on-site generation and caution for use. European Countries were pioneers of ozone use for potable water; the U.S.A. has been the groundbreaker for ozone use in municipal wastewater facilities (Robson and Rice, 1991).

The mechanism of disinfection depends on the considered pathogen. The inactivation of bacteria occurs through an oxidation reaction that leads to a degradation of the bacterial membrane followed by cellular lysis. Ozone may also disrupt enzymatic activity of bacteria by acting on sulphydryl groups in certain enzymes. With viruses the first sites of action are the proteic capsid used by the virion to fix on the cell surfaces and the nucleid acids. O_3 disinfection mechanism towards protozoan parasites like *Giardia* and *Cryptosporidium*, whose life cycle includes a fragile vegetative (trophozoite) and a stronger resting (cyst) stage, is still unclear. Ozone seems to have an effect on the cyst wall, making it permeable and damaging the plasma membrane (Langlais et al., 1991).

O_3 disinfection effectiveness is usually related to contact time (t) and disinfectant concentration (C) according to the well-known Chick's law (1908):

$$N(t)=N_0 \exp(-kC^n t) \qquad [1]$$

where N(t) and N_0 are the number of microorganisms surviving at time t and zero, k and n are the coefficient of specific lethality and dilution respectively. Applied ozone dosages between 5 and 20 ppm and contact times of 5-15 min, yielding 3 to 5 log inactivation, are usually reported for disinfecting municipal wastewater depending on the fixed microbial target (Singer, 1990). With such doses O_3 may oxidize potential organic DBP precursors and form relatively innocuous oxygenated DBP (e.g., organic acids) (Miltner et al., 1992).

Key factors affecting ozone disinfection are mass transfer efficiency, mixing, contact time and minimal short–circuiting as pursued with different ozonation system (e.g., diffused bubble, positive pressure injection, negative pressure or Venturi, packed tower). Although ozone is 12.5 times more water-soluble than oxygen, the low partial pressure available from commercial generators impairs O_3 effective mass transfer to the liquid phase (US-EPA, 1986; Grasso, 1990).

As with any other disinfectant, wastewater quality strongly affects O_3 disinfection performance, negatively influenced in particular by highly ozone-consuming soluble and/or suspended matter (Masschelein, 1991).

Materials and Methods

The investigation on ozone disinfection was carried out from June 1997 to January 1998 on a pilot plant purposely built at West Bari municipal wastewater treatment facility. This facility submits the sewage of approx. 300,000 inhabitants (3,000 m^3/h) to primary (mechanical screening and sedimentation, including pre-precipitation with $pAlCl_3$) and secondary (activated sludge followed by sedimentation) treatments. Approx. 20% of the secondary effluent undergoes also clarification (i.e., rapid mixing 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 (3-4 ppm of Cl_2) before discharge into the sea.

The clarified (CL) effluent was drawn to the pilot plant (see Figure 1) before chlorination. By filtration on a multilayer pressure filter (MF) filled with high purity silica sand and gravel a second effluent, namely the clarified-filtered (F) feed, was then obtained. The selected effluent was collected in a 5 m^3 fiber glass open vessel (RV) equipped with a slow speed (90 rpm) mechanical stirrer and feedback piping to control flow rate to ozonation, measured with a propeller flowmeter (FM1) and continuously monitored on a digital display.

Ozone disinfection 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 through the ejector (O3E) and the hydrokinetic mixer (O3M). The ozonated feed then entered the reaction tower (O3T) consisting of a 5 m^3 fiberglass vertical closed tank. Ozone was generated from air by high-tension (max. 15 kV) electric discharge in the production unit (O3P). This unit includes 6 vertical ozone generators, each bearing 14 replaceable glass pipes as dielectric and water-cooled high-tension electrodes, 2 high-tension transformers and 2 dryers. Sampling ports (1–6) were located at inlet and outlet of each individual piece of equipment.

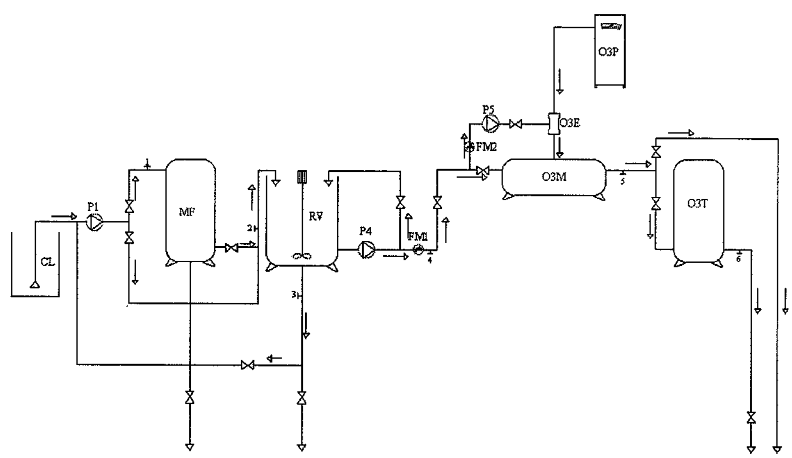


Figure 1. Pilot plant configuration during O_3 disinfection experiments

Dosage (ppm) was referred to applied ozone, of which approx. 90% was estimated to be transferred according to the ozonation equipment supplier (Cillichemie). Throughout the investigation ozone production was at max set point (445 g/h) while wastewater flow rate varied from 30 to 65 m^3/h with corresponding applied dosage ranging from 7 to 15 ppm, as reported in Table I. 30 m^3/h was the minimum wastewater flow rate required for a regular ozone production, so 15 ppm was the max ozone dosage applicable to wastewater with this system. Contact time up to 15 min was allowed. Ozone residual was not evaluated.

Table I. O_3 Dosages Investigated

Effluent flow rate (m^3/h)	O_3 flow rate (g/h)	O_3 applied dosage (ppm)
65	445	7
50	445	9
40	445	11
35	445	13
30	445	15

Both CL and F feeds were submitted to increasing disinfectant doses until the target microbial standards were achieved (if possible). During a single run, 5 m^3 of the selected feed collected in RV were added with the given O_3 dosage through the ejector O3E, mixed through the hydrokinetic mixer O3M and then collected batch wise in the reaction tower O3T for given contact times. Wastewater samples were collected after RV, soon after O3M (contact time of 0.1 min) and out of O3T (contact times of 5, 10 and 15 min) through sampling ports 4, 5 and 6.

For sake of reproducibility, each run was made in triplicate so that each cycle (i.e., one feed submitted to a given O_3 dose for a given contact time) took up approx. one full working day. Over 70 cycles were carried out according to the planned schedule.

Feed characteristics including Temperature, pH, Conductivity, Alkalinity, Total Suspended Solids (TSS), Turbidity, Total Dissolved Organic Carbon (TDOC), NH_4^+, $N\text{-}NO_3^-$, $N\text{-}NO_2^-$, Br^- and Total Coliforms before and after disinfection were analyzed routinely. Once the appropriate ozone dose was assessed, three more cycles were carried out in the same conditions in order to check for the parameters of agronomic interest in the disinfected effluent (pH, TSS, Sodium Adsorption Ratio, BOD_5, COD, Boron).

In addition, selected pathogens (*Nematodes* eggs, *Giardia lamblia* cysts, *Cryptosporidium parvum* oocysts and Pseudomonas *aeruginosa*) were monitored before and after disinfection. Finally, the eventual formation of DBP (i.e., total aldehydes, bromates and bromoform) was investigated.

Analytical procedures were according to Standard Methods (APHA et al., 1995), except for Sodium Adsorption Ratio (Pettygrove et al., 1985), *Pseudomonas aeruginosa*, *Giardia lamblia* cysts, *Cryptosporidium parvum* oocysts, *Nematodes* eggs (Liberti et al., 1998, 1999b) and total aldehydes (IRSA-CNR, 1994). In particular, the analytical method used for *Giardia* and *Cryptosporidium* (Standard Method No. 9711 B as modified by Portincasa *et al.*, 1997) involved pressure (4 atm) tangential ultra-filtration of a 10 l sample through 142 mm diameter (1.2 μm porosity) cellulose acetate membranes. The membranes were eluted with 0.1% Tween 80 solution under magnetic stirring and the eluant was centrifuged at 1500 rpm using plastic tubes. The resulting product was purified by Percoll-sucrose gradient and identified by microscopy using immunofluorescent monoclonal antibodies.

The following analytical instruments were used:

- gas chromatograph mod.8500 with head-space autosampler HS40 by Perkin Elmer;
- ionic chromatograph mod. 4500 I by Dionex;
- UV-visible spectrophotometer mod. Lambda 11 by Perkin Elmer;
- atomic absorption spectrophotometer (flame/graphite oven) mod. 400 by Varian;
- inductively coupled plasma (ICP) spectrometer mod. Optima 3000 by Perkin Elmer;
- TOC analyzer mod. 5050 by Shimadzu;
- vacuum concentration apparatus mod. AES 1000 by Savant;
- tangential ultra-filtration apparatus mod. Sartocon 2/Mini by Sartorius;
- fluorescence microscope mod. BH2 by Olympus;
- optic microscope mod. Axioskop MC 80 by Zeiss.

Results and Discussion

As shown in Table II, finite differences exist between the two feeds investigated, particularly among parameters more likely affecting disinfection performance such as TSS, Turbidity and Total Coliforms.

Table II. Main characteristics of clarified (CL) and clarified-filtered (F) feeds during the investigation

Parameter	CL			F		
	ave	min	max	ave	min	max
Temperature (°C)	22	17	27	20	18	22
pH	7.6	6.7	8.6	7.6	7.5	7.8
Conductivity (μS/cm)	2181	1590	6300	2979	1830	6330
Alkalinity (ppm $CaCO_3$)	322	280	416	300	194	380
Turbidity (NTU)	4.7	2.3	10.0	2.3	1.6	3.4
TSS (mg/l)	14	8	22	7	5	10
TDOC (mg/l)	7	3	16	7	4	9
NH_4^+ (mg/l)	23.3	11.5	35.5	21.5	14.3	35.9
$N\text{-}NO_3^-$ (mg/l)	0.22	0.01	1.20	0.76	0.10	3.13
$N\text{-}NO_2^-$ (mg/l)	0.45	0.01	1.24	0.51	0.02	1.24
Br^- (mg/l)	3.48	1.05	9.92	4.13	1.67	10.11
Total Coliforms 1000 (CFU/100ml)	1380	300	4550	700	240	1600

Disinfection Effectiveness

Main results of ozone disinfection effectiveness towards the two feeds investigated reported in Figures 2 and 3 clearly show that in the experimental conditions investigated ozonation did achieve the Italian microbial standard for unrestricted reuse of wastewater in agriculture (2 CFU/100ml for Total Coliforms) even with the "full

Title 22" (i.e., clarification + filtration + disinfection) nor, of course, with the simpler treatment (clarification + disinfection).

Although smaller O_3 dosages (1-5 ppm) were reportedly sufficient to reach such standard during disinfection of drinking water (Bourbigot, 1988), the same result was not achieved with municipal effluent since ozone oxidation power is rapidly consumed by fast chemical reactions occurring with organic and other oxidizable impurities unless the tertiary treatment includes clarification, sand-filtration and activated carbon adsorption (US-EPA, 1986).

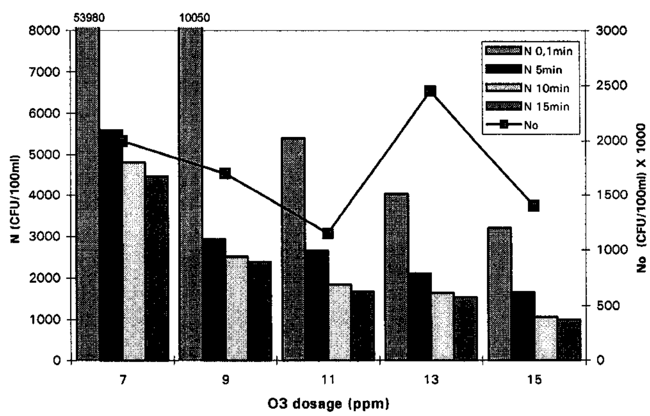


Figure 2. Total Coliforms inactivation during O_3 disinfection of clarified feed

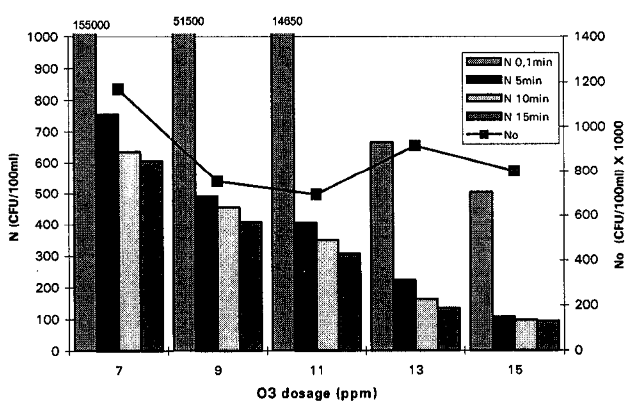
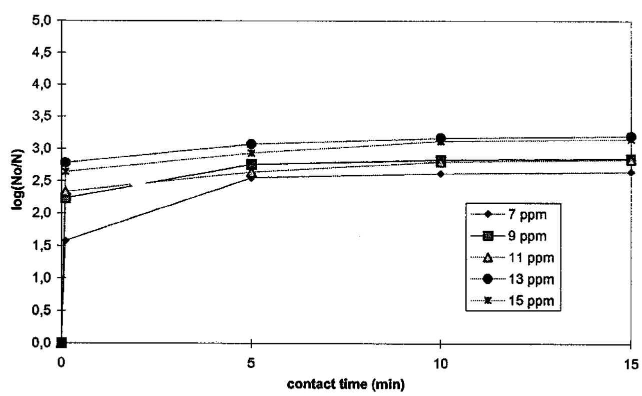


Figure 3. Total Coliforms inactivation during O_3 disinfection of clarified-filtered feed

On the contrary, the corresponding 1989 WHO guideline (1,000 CFU/100ml for Fecal Coliforms) was achieved with both feeds. In particular, with CL feed such target was reached only at the highest dosage (15 ppm) and 10 min contact time, whereas with F feed it was achieved even at the lowest ozone dosage investigated (7 ppm) and ≥ 5 min contact time. Furthermore, an appealing coliform value of 100 CFU/100ml was achieved treating F feed with 15 ppm dosage for ≥ 5 min contact time.

As indicated in Figures 4 and 5, the experimental inactivation rate always showed a very sharp initial slope (i.e., at 0.1 min seemingly regardless of feed quality) and reached almost completion after approx. 5 min, confirming the fast kinetics of ozone disinfection in the conditions investigated (Langlais et al., 1991). Log-inactivation values ≥ 3 and ≤ 4 were obtained for CL and F feeds respectively. Further investigation should focus on the 0.1-5 minute window assessing in detail the role of feed characteristics.

Figure 4. Inactivation rate during O_3 disinfection of clarified feed



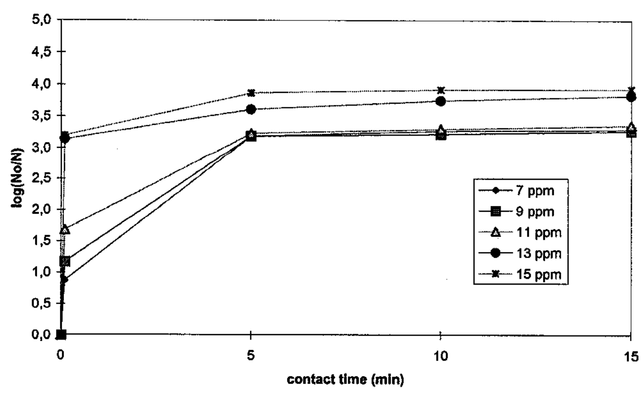


Figure 5. Inactivation rate during O_3 disinfection of clarified-filtered feed

Total Suspended Solids decreased and Total Dissolved Organic Carbon increased after ozone treatment of both feeds, as shown in Figure 6. Considering that microorganisms in wastewater can occur both in a free state and in the form of aggregates associated with solids, this should be explained with the organic nature of the particulate, wherein the oxidizable organic suspended material reacts with ozone to yield soluble organic products that slightly increase the TDOC of the ozonated effluent (Narkis, 1995).

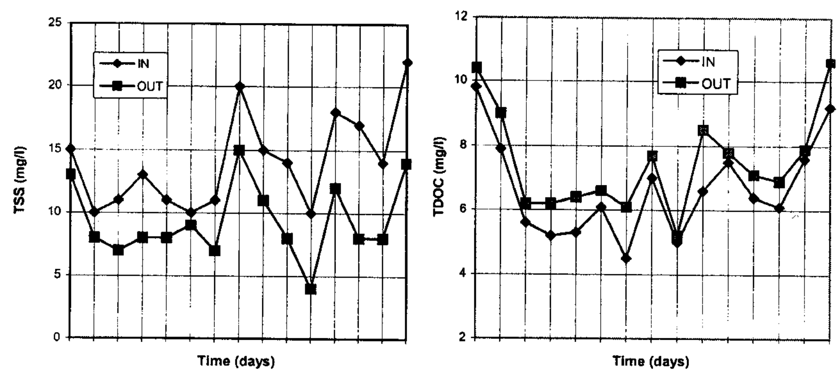


Figure 6. TSS decrease and TDOC increase after ozonation (15 ppm, 10 min) of CL feed

Effect on Selected Pathogens

Protozoa like *Cryptosporidium parvum* and *Giardia lamblia*, helminths like *Nematodes* and bacteria like *Pseudomonas aeruginosa*, commonly occurring in municipal wastewater, are of particular concern being resistant to chemical disinfection and causing potentially lethal diseases in immunocompromised population (Smith et al., 1995). The occurrence of these pathogens in CL and F feeds before and after ozonation (15 ppm applied dosage, 10 min contact time) is reported in Tab. III.

As indicated, *Nematodes* eggs were never found in both feeds before ozonation, confirming that heavy and large parasites are consistently removed by clarification and sedimentation treatments. On the contrary, an appreciable number of the smaller *Giardia* cysts, *Cryptosporidium* oocysts and *Pseudomonas* organisms were detected in CL feed and removed only in part by sand filtration, as expected (Bukhari, 1997).

The data in Table III also indicate that in both feeds O_3 was very effective towards Pseudomonas ($\geq$ 98% removal), rather effective towards *Giardia* ($\leq$ 60% removal) and scarcely effective towards *Cryptosporidium* ($\leq$ 14% removal). This partially agrees with literature data reporting ozone effectiveness towards *Crypto*, although the matter is still debated (Korich, 1990; Parker, 1993). The low concentration of oocysts in the feeds investigated, affecting the precision of microbiological measurements, could explain such different performance as already suggested (Parkhurst and Stern, 1998).

Table III. Selected pathogens before and after o_3 disinfection (15 ppm, 10 min)

Pathogen	Feed CL IN	Feed CL OUT	Feed F IN	Feed F OUT
Pseudomonas aeruginosa (CFU/100ml)	1800	28	800	8
Giardia lamblia cysts (N/l)	213	92	33	10
Cryptosporidium parvum oocysts (N/l)	10	8	2	2
Nematodes eggs (N/l)	0	0	0	0

DBP FORMATION

The reaction mechanism of O_3 with organics involves the direct reaction of its molecule or the intervention of less selective and much more reactive radical species. Both molecular and free radical ozone pathways resulting from its complex decomposition, as well as the nature of organic precursors, play a role in the possible formation of harmful DBP during ozonation (Langlais et al., 1992). A number of studies identified several ozone DBPs like mono- and dicarboxylic acids, mono- and diketones, alkanes, phthalates, organic peroxides, epoxides and aldehydes (Minear and Amy, 1996). Among these latter, 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, 1995). In 1995 bromates and brominated THMs, potentially formed during the ozonation of Br^- containing waters, were included in the European list of potentially toxic DBP (European Commission, 1995). Since both feeds investigated contained approx. 4 ppm of bromide ions (see Table II), bromate (BrO_3^-) and bromoform ($CHBr_3$) in addition to aldehydes formation was also checked for during the present investigation.

Figure 7 indicates a similar, although limited, increase of Total Aldehydes (approx. 350 ppb measured as sum parameter) for both feeds, clearly related to their similar TDOC content (7 ppm) and ozone dose.

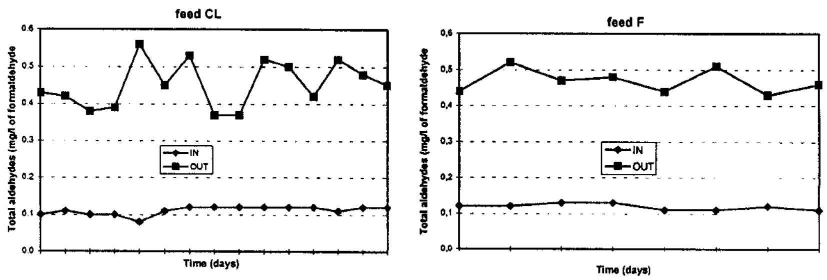


Figure 7. Total Aldehydes increase after ozonation (15 ppm, 10 min)

No appreciable bromate or bromoform formation was noticed after the ozonation of both feeds. In particular bromoform, already present in trace (0.3 and 0.5 ppb in CL and F, respectively), remained constant during ozonation whereas bromate ions were never detected. These results can be explained considering the following reactions potentially occurring during the ozonation of wastewater containing bromide ions (Glaze et al., 1993; Siddiqui et al., 1995):

$$O_3 + Br^- = O_2 + BrO^- \qquad (k=160\ M^{-1}s^{-1}) \qquad [2]$$

$$2O_3 + BrO^- = 2O_2 + BrO_3^- \qquad (k=100\ M^{-1}s^{-1}) \qquad [3]$$

$$H^+ + BrO^- = HBrO \qquad (pK_a = 8.8) \qquad [4]$$

$$HBrO + \text{organic matter} = CHBr_3 \qquad (k=20\ M^{-1}s^{-1}) \qquad [5]$$

According to Equation [4], the undissociated hypobromous acid (HBrO) prevailed in the conditions investigated (pH < 8.8 in both feeds, see Table II), hence, while oxidation to BrO_3^- was unlikely, appreciable bromoform formation was expected. In fact, even this latter was prevented by the fast competing bromamination reaction:

$$HBrO + NH_3 = NH_2Br + H_2O \qquad (k=8\cdot 10^7\ M^{-1}s^{-1}) \qquad [6]$$

$$NH_4^+ = NH_3 + H^+ \qquad (pK_a = 9.3) \qquad [7]$$

Both feeds indeed contained ammonia (22-23 ppm of NH_4^+) quickly converted to monobromamine thus avoiding bromoform formation (Von Gunten and Hoignè, 1992; Siddiqui and Amy, 1993).

Compliance with Agronomic Regulation

Table IV reports the characteristics of both feeds after ozone disinfection (15 ppm, 10 min) with reference to the parameters of agronomic interest for reuse of municipal wastewater in agriculture, according to Italian regulation. As shown, compliance was always achieved for all parameters except Total Coliforms.

Furthermore, the survival of some protozoa (*Giardia* cysts and *Cryptosporidium* oocysts) in the disinfected effluents does not cause restriction for their reuse in agriculture. In fact, according to WHO (1989), the only parasites of concern are the intestinal *nematodes* (MAC < 1 egg/l), neither found after clarification nor clarification and filtration during this investigation.

Table IV. Agronomic characteristics of Cl and F feeds after O_3 disinfection (15 ppm, 10 min)

Parameter	feed	O_3 effluent	MAC°
pH	F	7,8	5,5-9,5
	CL	7,7	
TSS (mg/l)	F	6	80
	CL	10	
BOD5 (mg/l)	F	4	40
	CL	5	
COD (mg/l)	F	51	160
	CL	59	
Boron (mg/l)	F	0,8	2
	CL	0,9	
Sodium Adsorption Ratio	F	7	15
	CL	7	
Total Coliforms (CFU/100ml)	F	97	2*-20**
	CL	1060	

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

* for crops to be eaten uncooked

** for crops to be eaten cooked and for irrigation of pastures or meadows

Cost Estimates

On the basis of the experimental results obtained, O&M costs of tertiary effluent disinfection with O_3 were preliminarily estimated by reference to an ozone applied dosage of 15 ppm, required to achieve the WHO 1,000 CFU/100ml Fecal Coliform guideline with CL feed and the more appealing 100 CFU/100ml coliform value with F feed.

The following assumptions were made:

- O&M costs are due essentially to power consumption and O_3 generator replacement, including also miscellaneous equipment repair;
- 1 kWhr costs 0.065 EURO;
- power consumption of O_3 equipment is 15.8 kWhr;

- O_3 generator (400 EURO/each) lasts approx. 26,000 hours.

As shown in Table V, O&M costs of O_3 advanced disinfection for municipal wastewater reuse in agriculture average 37 Euro/1000m^3. The above estimates do not include capital costs and can be influenced by a wide range of variables, such as feed quality, plant configuration, plant size (scale factor) and market situation.

Table V. Cost Estimates for O_3 disinfection (15 ppm, 10 min) of Cl and F feeds at West Bari Pilot Plant

Operation & Maintenance costs	(Euro/1000m^3)
Electric power	34.2
O_3 generator replacement	3.1
Total	**37.3**

For sake of comparison, chlorination of wastewater for sea discharge in compliance with Italian regulations (20,000 CFU/100ml for Total Coliforms) at West Bari municipal plant costs ≤ 5 Euro/1000m^3.

Conclusions

The pilot plant operated at West Bari (Southern Italy) municipal wastewater treatment facility from June 1997 to January 1998 permitted a field evaluation of Ozone as alternative method for advanced disinfection of municipal wastewater for reuse in agriculture. The experimental results obtained with two tertiary effluents of different quality, namely *clarified-filtered* (F) (i.e., "full Title 22") or just *clarified* (CL), provided the following indications:

- Total Coliforms standard of 2 CFU/100ml required by the Italian regulation (based on the well known 1978 California Wastewater Reclamation Criteria) was never achieved in the experimental conditions investigated (7-15 ppm O_3 applied dosages, up to 15 min contact time) with either feed. Conversely, WHO guideline (1,000 CFU/100ml for Fecal Coliforms) was achieved for CL feed with 15 ppm of O_3 and for F feed with 7 ppm, always providing contact times ≥ 5 min. With the latter feed, furthermore, the appealing figure of 100 CFU/100ml for Total Coliform was also met at 15 ppm of O_3 and ≥ 5 min.
- Ozone disinfection kinetics was very fast, almost completed after 5 min.
- 3 and 4 log-inactivation values were achieved with CL and F feed respectively.
- Ozone dosage of 15 ppm was very effective towards *Pseudomonas aeruginosa* (≥ 98% removal), rather effective towards *Giardia lamblia* (≤ 60%) and scarcely effective towards *Cryptosporidium parvum* (≤ 14%), although a final conclusion on this latter pathogen was prevented by the low number of its oocysts in the feeds; *Nematodes* eggs were never found before disinfection.
- Limited formation of disinfection by-products (approx. 350 ppb of total aldehydes) followed ozonation (15 ppm) of both feeds. Even in the presence of 4 ppm of

bromide ions, neither bromate or bromoform formation was detected, probably due to the pH value (7.6) and the ammonia concentration (22-23 mg/l) of both feeds.

- All parameters of agronomic interest (pH, TSS, BOD_5, COD, SAR and Boron) except Total Coliforms complied with Italian regulations for wastewater reuse.
- O&M costs of ozonation (15 ppm) averaged 37 Euro/1000m^3.

Further investigation is planned on the following major aspects:

- improvement of O_3 gas transfer efficiency to the liquid phase;
- bacteria inactivation at very low contact times (0.1-5 minutes);
- effect of O_3 on survival of *Cryptosporidium parvum* oocysts;
- more extensive search for possible DBP formation;
- possible synergy and/or catalytic effects of O_3 with other chemical disinfectants such as H_2O_2 or peracetic acid;
- ozonation of full tertiary municipal wastewater (clarified, sand filtered and GAC adsorbed);

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Key Words

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