Advanced treatment for municipal wastewater reuse in agriculture. UV disinfection: bacteria inactivation

Lorenzo Liberti, Michele Notarnicola, Giancarlo Boghetich and Antonio Lopez

ABSTRACT

A 100 $m^3 h^{-1}$ pilot plant was built at West Bari (southern Italy) Wastewater Treatment Plant and operated from 1996 to 1998 to compare bacteria inactivation, parasite removal, disinfection by-products formation and cost effectiveness of advanced disinfection methods such as UV rays, peracetic acid and ozone, alone or in proper combination, on differently treated municipal effluents. This paper reports the bacteria inactivation effectiveness of UV disinfection of secondary (II), secondary-clarified (CL) or secondary-clarified-filtered (F) effluent for meeting the Italian microbial standard for unrestricted reuse of municipal wastewater in agriculture (2 CFU 100 ml-1 of total coliforms). Such a 5 log inactivation target was effectively met with F and CL effluents at a dose of 100 and 160 mWs cm^{-2} respectively, while it was only almost approached with effluent II at 430 mWs cm^{-2} dose. Significant removal of disinfection-resistant bacteria like *Pseudomonas aeruginosa* as well as full compliance with local agronomic regulation also was achieved for both CL and F disinfected effluents.

Key words | bacteria inactivation, disinfection, tertiary treatment, total coliforms, UV rays, wastewater reuse

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INTRODUCTION

Growing water demand in semi-arid areas bordering the Mediterranean Sea makes agricultural reuse of municipal wastewater compulsory for the 21st century. Various schemes of *advanced* (or *tertiary*) treatment have been proposed in the last two decades with the so-called 'full Title 22' scheme, that is, secondary effluent further submitted to clariflocculation, sand filtration and final disinfection (State of California 1978), most often adopted so far. However, accounting for its energetic 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). Due to the presence of pathogens, advanced disinfection is crucial to make such a choice viable. After the pioneering demonstration that chlorination may produce harmful chloro-organic disinfection by-products (DBP) (Rook 1974), alternative disinfectants are being considered worldwide for meeting the stringent sanitary standards usually required for wastewater reuse (WPCF 1986; WEF 1996; IWSA 1997).

With these objectives, that is, to find cheaper advanced treatment and safer disinfection methods than chlorination, a 3-year international project involving research teams from Israel, Malta, Morocco, Spain, UK and Italy was started in 1996 financed in part by the European Commission under the Avicenne Initiative (Project No. AVI-CT94-0010). The Italian team was committed mainly to comparing the effectiveness of alternative disinfection methods such as ultraviolet rays (UV), peracetic acid (PAA) and ozone (O_3). A 100 $m^3 h^{-1}$ pilot plant fully equipped for disinfecting municipal effluent with the above methods was built at West Bari (southern Italy) municipal wastewater treatment plant from which two final effluents could be drawn before chlorination:

one following secondary sedimentation (*secondary* effluent, II), the other further undergoing post-precipitation with aluminium polychloride (*secondary-clarified* effluent, CL). The pilot plant was also equipped with sand filtration. Accordingly, three feeds, indicated as II, CL and F (*secondary-clarified-filtered*), were alternatively treated with the three disinfectants (UV, PAA, O_3).

The general results of the investigation as well as those concerning peracetic acid and ozone disinfection have been already published (Liberti & Notarnicola 1999; Liberti *et al.* 1999, 2000).

This paper reports on the investigation of UV disinfection of the above municipal effluents carried out from June 1996 to February 1997 with the specific objectives of:

- investigating the influence of wastewater characteristics on disinfection performance;
- assessing the UV dose required for meeting the Italian microbial standard (2 CFU 100 ml^{-1} of total coliforms, based on the well known Wastewater Reclamation Criteria iof the State of California 1978) for unrestricted reuse of wastewater in agriculture, paying special attention also to resistant bacteria like *Pseudomonas aeruginosa*;
- complying with wastewater quality parameters Italian agronomic regulation.

UV DISINFECTION

The disinfection capability of ultraviolet rays associated with sunlight has long been recognized and radiation at a wavelength in the range of 240–280 nm shows finite biocidal efficiency. This can be artificially achieved through electric discharge in low-pressure Hg vapour lamps capable of efficiently converting approx. 85% of electric energy to light emitted at a characteristic wavelength of 253.7 nm. More recently, medium-pressure lamps have been developed, yielding a higher intensity across a broader spectrum of the biocidal range (WERF 1995).

Although ultraviolet light is not as widely used yet as *chemical* disinfectants like chlorine and/or ozone to disinfect wastewater, there is considerable evidence that this *physical* method may become a reliable alternative to them. Its main advantages lie in the high degree of broad-spectrum disinfectant action, relative technological simplicity, very fast kinetics (contact times of few seconds), claimed lack of DBP formation and cost effectiveness at doses commonly used in drinking and wastewater treatment (WEF 1998).

UV disinfection is unique in its mode of action. In fact, while chemical disinfectants predominantly kill microbial organisms by disrupting their cell functions, the germicidal mechanism of UV radiation involves photochemical damage to RNA and DNA within the cell, so that the organisms can no longer reproduce (Jagger 1967; US-EPA 1992). However, under appropriate conditions (i.e. immediate exposure to sunlight, abundance of carbonaceous metabolites) certain microorganisms (e.g. coliform indicators) exhibit the capability to repair their DNA damage and reactivate (*cell repair* and *photoreactivation* phenomena). In addition, UV radiation provides no residual disinfecting capability. Therefore, a chemical persistent disinfectant (usually <1 mg l^{-1} of Cl_2 or H_2O_2) must be added to protect the distribution system ensuring bacteriostatic action and preventing bacterial regrowth (Wolfe 1990). Italian regulation, in particular, requires a limited post-chlorination to warrant a 0.2 mg l^{-1} of residual Cl_2 in the disinfected effluent.

The kinetics of *physical* disinfection methods like UV may be approximated by a first order expression based on the well known Chick and Watson law:

$$N_t = N_0 \exp(-kIt) \quad (1)$$

where N_0 and N_t are the number of initial microorganisms and the number surviving at exposure time t (s), respectively, k is the inactivation rate constant ($cm^2\ mW^{-1}s^{-1}$) and I is the intensity of the UV light energy (mW cm^{-2}).

In principle no microorganisms should reproduce if sufficient UV dose is applied and this is particularly useful for pathogens which are less sensitive to chlorine (Snider *et al.* 1991; WERF 1995). At doses <100 mWs cm^{-2} UV is highly efficient towards viral and bacterial pathogens (Bryant *et al.* 1992); also more resistant protozoan parasites like *Giardia lamblia* and *Cryptosporidium parvum*, reportedly requiring higher doses (<200 mWs cm^{-2}) for

their removal (Karanis *et al.* 1992; Campbell *et al.* 1995), recently underwent effective inactivation at very low UV doses with advanced medium-pressure lamps (Clancy *et al.* 1998).

UV disinfection is strongly influenced by the actual radiation pattern and the associated geometry of the systems, either *submerged* (in-channel and enclosed lamp) or *unsubmerged* according to the water-lamps contact configuration (Hoyer *et al.* 1992). Radiation is strongly diminished by the inherent absorbance, that is, by colour and turbidity, of the effluent to be disinfected (US-EPA 1992). Hence water must be previously treated to remove particulate matter that might shield pathogenic organisms as well as to reduce colour and other substances that can absorb UV radiation (Emerick & Darby 1993). Careful lamp cleaning must be provided, depending on the wastewater scaling aptitude, that is, hardness, alkalinity, iron, manganese and other constituents that may form precipitates.

In conclusion, UV radiation is claimed to show very fast bactericide efficiency towards a wide variety of viable species, to prevent the formation of toxic DBP, to avoid noxious taste and smell with no need for handling, storage and disposal of hazardous chemicals, and reasonable costs (investment and operation). Major drawbacks are absence of bacteriostatic effect, possibility of water recontamination by cell repair and photoreactivation phenomena, unfavourable influence of water characteristics such as turbidity, suspended solids, colour, colloidal matter and dissolved organics (shelter, scattering and absorption effects) and decline of UV output intensity with lamps scaling and age.

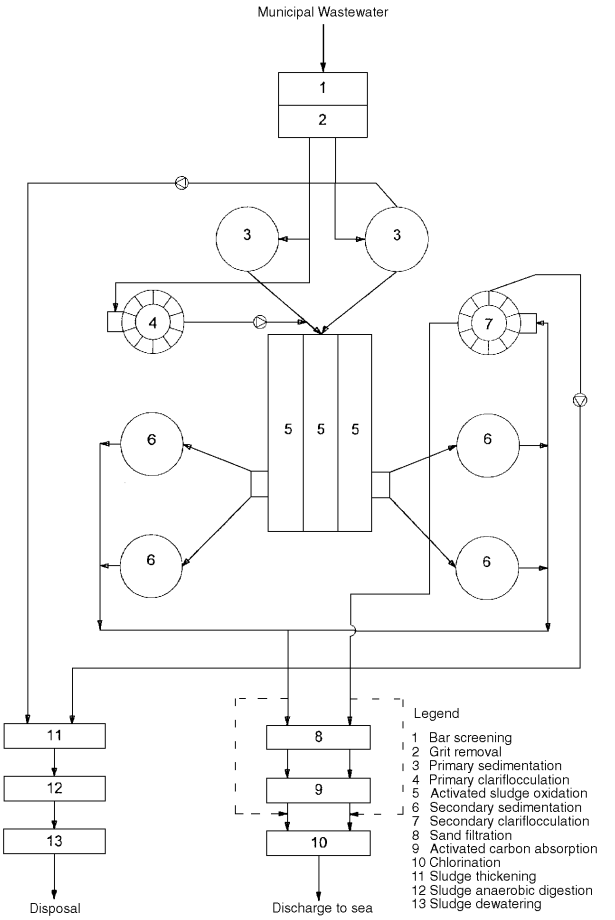


Figure 1 | Flow-sheet of West Bari municipal wastewater treatment plant (3,000 $m^3\ h^{-1}$).

MATERIALS AND METHODS

West Bari municipal plant (see Figure 1) treats mixed sewage (civil plus industrial) from a population of approximately 300,000 inhabitants (3,000 $m^3\ h^{-1}$) by primary (mechanical screening and sedimentation, including pre-precipitation with $pAlCl_3$) and secondary treatments ('carousel' activated sludge followed by 6 h sedimentation at a hydraulic linear velocity of 0.9 m h^{-1}). A fraction of the secondary effluent (approx. 600 $m^3\ h^{-1}$) also undergoes post-precipitation through coagulation and flocculation with 30–40 mg l^{-1} $pAlCl_3$ and ≤2 mg l^{-1} polyelectrolyte followed by sedimentation. Although installed, further expensive steps towards 'full Title 22' tertiary treatment for agricultural reuse (i.e. sand filtration and GAC adsorption) are actually by-passed and, after disinfection by chlorination (3–4 ppm of Cl_2), the final effluent is discharged through a long (1.7 km) marine outfall.

Figure 2 shows the pilot plant configuration during UV experiments. It permits a comparison of the performance of UV disinfection with feeds of increasing quality. Unchlorinated secondary (II) and clarified (CL) feeds were drawn directly from the West Bari plant by means of

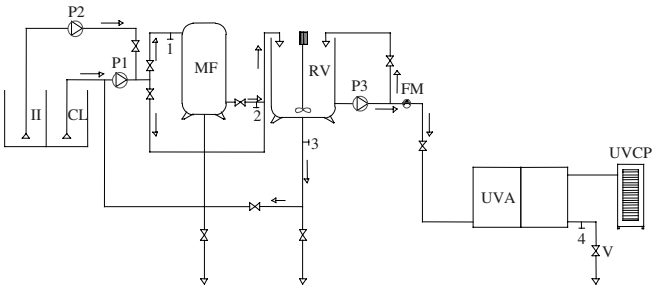


Figure 2 | Flow-sheet of the pilot plant configuration during UV disinfection tests.

P2 or P1 pumps respectively. The clarified-filtered feed (F) was obtained by filtering CL on a multilayer pressure filter (MF, mod. CILLIT SF10, flow rate 10 m^3 h^{-1}, filtering bed 120 cm of 0.4–0.7 mm high purity silica sand and 1–2, 3–5 and 6–8 mm gravel). The selected feed (II, CL or F) was first collected in a 5 m^3 fibre-glass vessel (RV) equipped with a mechanical stirrer to be eventually homogenized (in fact, the wastewater equalization ensured by West Bari plant made further homogenization seldom necessary) and then continuously fed with a P3 pump to the UV apparatus (UVA) at a flow rate, regulated by valve V, corresponding to the desired UV dose. Sampling ports 1 to 4 allow for sample collection and analysis before and after disinfection. P1, P2 and P3 are self-priming centrifugal pumps already employed at West Bari treatment plant.

A *non-contact* Teflon UV apparatus (UVA, mod. 600 L Super, maximum flow rate 140 m^3 h^{-1}, kindly provided by UVT, Taranto, Italy) was used wherein the water flow splits between 15 parallel, inverted, U-shaped Teflon tubes (Figure 3). These were surrounded externally by 62 low pressure (0.2 atm or 0.2×10^5 N/m^2) Hg vapour lamps emitting UV radiation at 253.7 nm with a nominal intensity of 30 mW cm^{-2}. The UVA was wired by a control panel (UVCP).

UV dose D (mWs cm^{-2}) was calculated by the formula:

$$D = It \tag{2}$$

where I is the average UV intensity inside the Teflon tubes (mW cm^{-2}) and t is the exposure time (s).

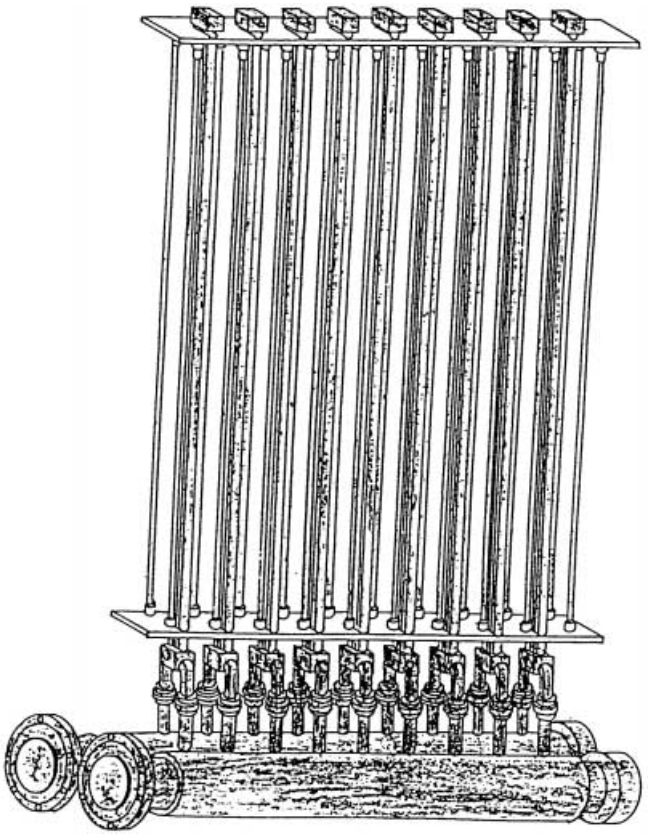


Figure 3 | Scheme of the UV Apparatus (mod. 600 L Super, courtesy of UVT).

Accounting for the difficulty of evaluating I precisely (Hoyer *et al.* 1992; Schoenen 1996), this was estimated by a probe measuring UV intensity at the inner tube wall (I_1) and correcting this value for both feed transmittance at 254 nm (tr) and tube diameter (6 cm) according to:

$$I = (I_1 + I_2 + I_3 + I_4)/4 \tag{3}$$

where $I_2 = \mathrm{tr}\, I_1$, $I_3 = \mathrm{tr} \times I_2$ and $I_4 = \mathrm{tr} \times I_3$ are the intensity values respectively at 1, 2 and 3 cm from the inner tube wall. During the investigation on feeds F, CL and II the average values of I_1 and tr were 20, 18 and 17.5 mW cm^{-2} and 67, 61 and 55% cm^{-1} respectively, yielding a corresponding I value around 12, 10 and 9 mW cm^{-2}.

Exposure time (t) inside the UV reactor was related directly to hydraulic retention time (i.e. flow rate referred to the reactor volume actually exposed to UV light). By decreasing flow rate from 100 to 5 m^3 h^{-1} (minimum

Table 1 | Flow-rates, exposure times, average UV intensities and UV doses during the investigation

Feed	Flow rate ($m^3 h^{-1}$)	Exposure time (s)	Avg. UV intensity ($mW cm^{-2}$)	UV dose ($mWs cm^{-2}$)
F	100	2.5		30
	80	3.1		40
	70	3.5		45
	60	4.1	12.2	50
	50	4.9		60
	40	6.1		75
	30	8.2		100
CL	50	4.9		50
	40	6.1		60
	35	7.0		70
	30	8.2	9.9	80
	25	9.8		100
	20	12.2		120
	15	16.4		160
II	15	16.4		145
	10	24.4	8.8	215
	5	48.8		430

wastewater flow rate required to guarantee a regular flow in the UV apparatus) it was possible to change exposure time from 2.5 to approx. 50 s with corresponding UV doses ranging from 30 to 430 mWs cm^{-2}. Experimental conditions during the UV tests are summarized in Table 1.

First the best feed (i.e. secondary-clarified-filtered, F) was submitted to increasing UV doses until the target count of 2 CFU 100 ml^{-1} of total coliforms was achieved (if possible). When this occurred, the poorer feeds (i.e. secondary-clarified, CL and secondary, II, in that order) were then treated similarly. Each run started by filling vessel RV with 5 m^3 of the selected effluent. The feed was then continuously conveyed to the UV apparatus at the given flow rate and exposed to the corresponding UV dose. The run was then repeated under the same conditions in order to average triplicate results for each UV dose, so that each cycle (i.e. a given feed submitted to a given dose) took up approx. half a working day. At the end of each cycle the filter MF (if used) was backwashed and filled up with a 20 ppm NaOCl tap water solution. Before starting a new cycle the whole pilot plant was thoroughly rinsed with tap water until the chlorine residue disappeared, checking as well for absence of microbial activity. A total of 90 cycles were carried out in the 9 months of investigation (from June 1996 to February 1997), according to the planned schedule and using the appropriate configuration of the pilot plant. The UV lamps were never turned off throughout this period and the Teflon tubes were cleaned once before beginning the investigation.

The following feed characteristics were routinely analysed: temperature, pH, conductivity, turbidity, total suspended solids (TSS), total dissolved organic carbon (TDOC), 254 nm transmittance, $N\text{-}NH_4$, $N\text{-}NO_3$, $N\text{-}NO_2$ and total coliforms (before and after disinfection). Once (if) the UV dose necessary for achieving the target 2 CFU 100 ml^{-1} total coliforms standard on the given feed was found (single demonstrations according to discontinuity of pilot tests), six more cycles were carried out at that dose to check for pathogenic bacteria like *Pseudomonas aeruginosa* before and after UV disinfection. Furthermore, the parameters of agronomic interest (pH, TSS, BOD_5, COD, boron, sodium adsorption ratio and total coliforms) were determined in the disinfected effluents.

Representative samples for feed characterization were taken from proper sampling ports; all disinfected samples were grab collected downstream of the UV apparatus. Samples for physico-chemical analyses were collected in amber polyethylene bottles and immediately placed in a portable refrigerator. Samples for microbiological analyses were collected in autoclaved glass bottles after sterilizing the sampling ports with a portable flame.

Table 2 | Main average characteristics of secondary (II), clarified (CL) and clarified-filtered (F) feeds during the investigation

	II			CL			F		
	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max
Temperature (°C)	18	17	19	19	16	23	22	20	23
pH	7.6	7.5	7.7	7.7	7.5	7.8	7.7	7.2	8.0
Conductivity ($\mu S\ cm^{-1}$)	1842	1560	2390	1891	1271	2360	1843	1470	2300
Turbidity (NTU)	8.1	5.9	29.3	4.9	3.1	9.8	1.6	1.2	2.4
TSS ($mg\ l^{-1}$)	21	12	36	12	7	23	4	3	5
TDOC ($mg\ l^{-1}$)	9	5	13	11	6	20	17	13	23
254 nm transmittance (%)	55	49	60	61	56	66	67	60	70
NH4 ($mg\ l^{-1}$)	28.1	21	43.4	27.6	16.7	34	27.8	22.6	50.5
N-NO3 ($mg\ l^{-1}$)	1.32	0.36	3.58	0.6	0.11	1.59	0.75	0.1	2.51
N-NO2 ($mg\ l^{-1}$)	0.39	0.08	0.72	0.22	0.1	0.35	0.22	0.01	0.71
Total coliforms 1000 (CFU $100\ ml^{-1}$)	908	210	3700	715	100	2000	162	0.2	620

Standard analytical procedures (*Standard Methods* 1995) were used during the investigation except for the following:

- *Pseudomonas aeruginosa*: membrane filter technique (Standard Method No. 9213 E) with agar cetrimmide as culture medium;
- *UV transmittance at 254 nm*: sample transmittance through a 1 cm width optical glass cuvette was measured by a spectrophotometer at wavelength 254 nm with instrument zero set by distilled water;
- *Sodium adsorption ratio (SAR)*: evaluated according to Pettygrove & Asano (1985).

The following analytical instruments were employed:

- membrane filter technique kit;
- UV-visible spectrophotometer mod. Lambda 11 by Perkin Elmer;
- TOC analyser mod. 5050 by Shimadzu;
- atomic absorption spectrophotometer (flame and graphite oven) mod. 400 Plus by Varian;
- Inductively coupled plasma spectrometer mod. Optima 3000 by Perkin Elmer.

RESULTS AND DISCUSSION

Feed characteristics

UV light's effectiveness is significantly affected by water quality. In the case of municipal wastewater, a partial or even full tertiary treatment (i.e. 'Title 22' scheme) is usually required before UV disinfection. Table 2 compares the main characteristics of the three investigated feeds throughout the investigation period, clearly showing the finite quality improvement among II, CL and F effluents, particularly for parameters likely to affect UV disinfection performance such as turbidity, TSS, transmittance and total coliforms.

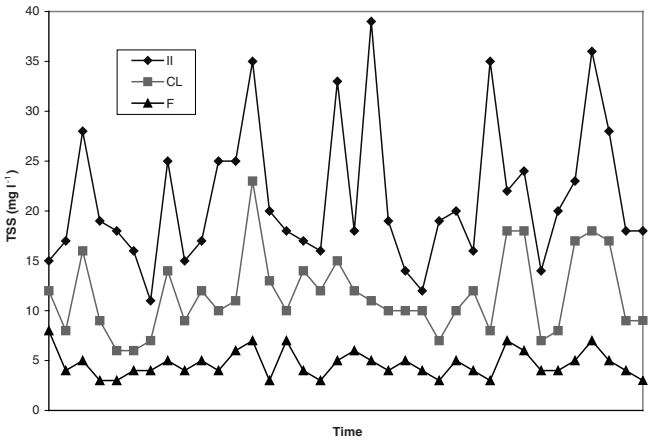


Figure 4 | Effect of clarification and filtration on TSS of secondary (II) feed.

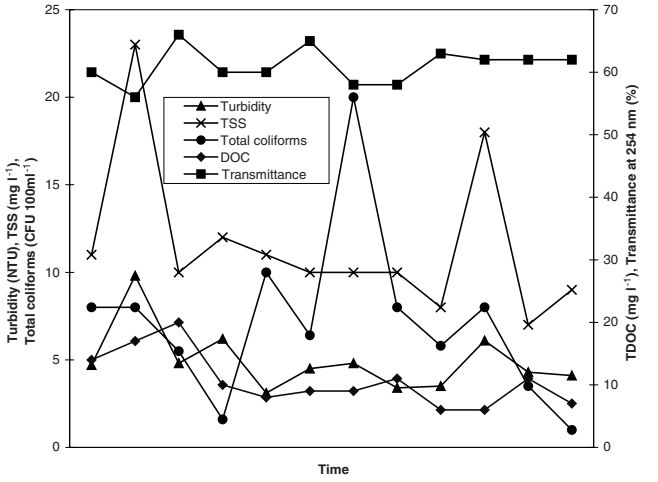


Figure 5 | Trends of main characteristics of clarified (CL) feed during the investigation.

In particular, Figure 4 shows the improving effect of the clarification and filtration step in decreasing the TSS content of effluent II.

Considering the variation with time for the above parameters during the investigation (see Figure 5 for feed CL) it appears that, apart from the single feed, the content of total coliforms was rather irregular. TSS and turbidity trends, in contrast, were very similar, suggesting that, for each feed, turbidity was related to TSS rather than to colloidal matter such as microorganisms.

Taking into account that UV disinfection is mainly affected by transmittance, which in turn is negatively influenced by turbidity, this confirms a major role played in this case by TSS on UV performance, in agreement with literature data (Emerick & Darby 1993; Andreadakis *et al.* 1999). Furthermore, except for total coliforms, the clarification step alone seemed quite effective at producing almost constantly a good quality effluent well suited for UV disinfection.

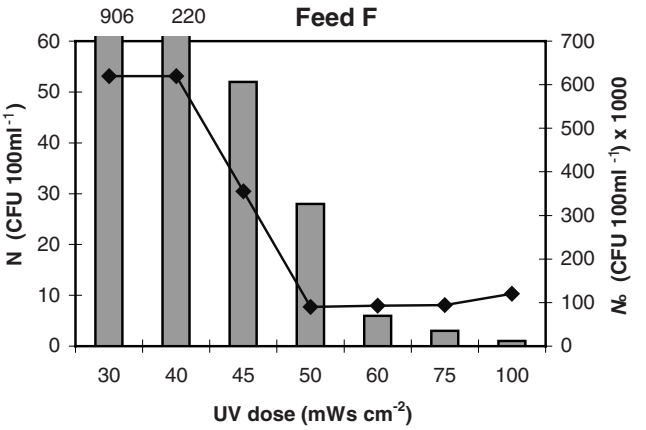
Disinfection performance

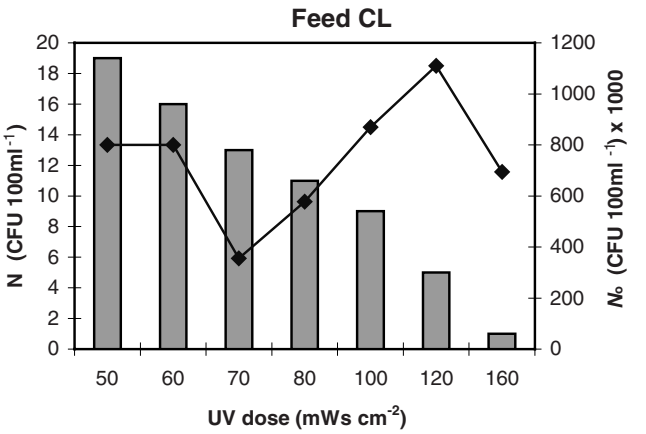
As already stated, the experimental tests in this investigation were aimed at assessing the possibility of using UV disinfection for meeting the stringent microbial standard for unrestricted reuse of municipal wastewater in agriculture, using either the 'full Title 22' treatment (i.e. clarification + filtration) or avoiding one or both steps. To this aim, F, CL and II effluents were submitted to increasing UV doses shown in Table 1.

Figure 6 summarizes the most relevant results concerning total coliforms inactivation effectiveness on various feeds. These data indicate that the target standard was effectively achieved not only with the best (F) but also with the intermediate (CL) quality feed at 100 and 160 mWs cm^{-2} UV dose respectively. The first value falls in the range 100–120 mWs cm^{-2} reported in literature for clarified-filtered feeds (Awad *et al.* 1993; Chen *et al.* 1993) and the second is rather lower than the 200–240 mWs cm^{-2} reported for clarified feeds in previous investigations (Snider *et al.* 1991; Chen *et al.* 1993). It was concluded that, under the experimental conditions investigated, even the most stringent 2 CFU 100 ml^{-1} coliform standard could be met by UV disinfection of clarified secondary effluent, avoiding expensive filtration yielding 'full Title 22' effluent.

Furthermore, a very appealing result (≤10 CFU 100 ml^{-1} of total coliforms) was obtained with the poorest quality feed (II) at the maximum UV dose investigated (430 mWs cm^{-2}), even if the target was not met and the initial coliform content ($<1 \times 10^6$ CFU 100 ml^{-1}) was not representative of a typical biologically treated secondary effluent (some millions CFU 100 ml^{-1}).

In Figure 7 experimental UV disinfection performance is also reported in terms of log inactivation, that is, log of





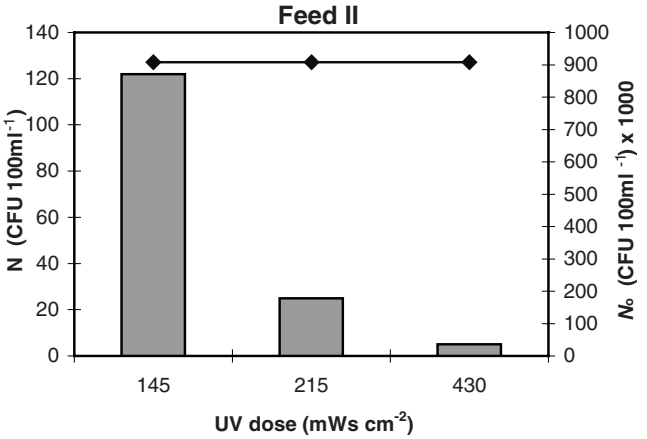


Figure 6 | Disinfection effectiveness of UV on total coliforms during the investigation (II, secondary; CL, clarified; F, clarified-filtered).

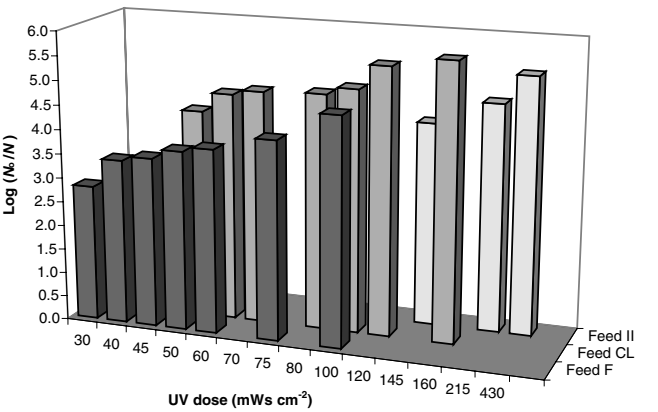


Figure 7 | Total coliforms log-inactivation with UV during the investigation (II, secondary; CL, clarified; F, clarified-filtered).

Table 3 | *Pseudomonas aeruginosa* before and after UV disinfection of F and CL feeds (dose 100 and 160 mWs cm^{-2} respectively)

	Feed F		Feed CL	
Pathogen	**In**	**Out**	**In**	**Out**
Pseudomonas aeruginosa (CFU 100 ml^{-1})	20,000	1	130,000	2

the influent (N_0) to effluent (N) total coliforms ratio. From these data it appears that, by reference to the 4 log target commonly required for advanced disinfection, an UV dose as low as 50, 75 and 145 mWs cm^{-2} is adequate to consistently disinfect CL, F and II feed respectively. Moreover, very appealing 4.7 and 5.7 log reduction values resulted from the higher doses (100 and 160 mWs cm^{-2} respectively) required by F and CL feeds to meet the 2 CFU 100 ml^{-1} coliform standard, confirming that this latter really drives the dose requirement up (Oppenheimer *et al.* 1997).

Finally, UV *physical* disinfection, as expected, showed extremely fast kinetics (contact time ≤20 s for feeds F and CL) compared with *chemical* disinfection requiring several minutes.

Table 3 reports the occurrence of *Pseudomonas aeruginosa* before and after UV disinfection during specific cycles carried out on F and CL feeds at doses necessary for achieving the microbial standard for unrestricted reuse of

Table 4 | Agronomic characteristics of F and CL feeds after UV disinfection (dose 100 and 160 mWs cm^{-2} respectively)

Parameter	Feed F	Feed CL	MAC[a]
pH	8.1	7.8	5.5–9.5
TSS (mg l^{-1})	3	8	80
BOD_5 (mg l^{-1})	10	5	40
COD (mg l^{-1})	40	57	160
Boron (mg l^{-1})	1.3	0.9	2
Sodium adsorption ratio	6	6	15
Total coliforms (CFU 100 ml^{-1})	1	1	2[b]–20[c]

[a]Maximum allowable concentration for agricultural reuse (L.319/76, DCI 4/2/77).
[b]For crops to be eaten uncooked (unrestricted reuse).
[c]For crops to be eaten cooked and for irrigation of pastures or meadows (restricted reuse).

wastewater in agriculture (i.e. 100 and 160 mWs cm^{-2} respectively). UV was very effective in removing these pathogenic bacteria, reportedly very resistant to disinfection (Hassen *et al.* 2000), providing log inactivation values >4 and <5 respectively for F and CL feed.

Compliance with agronomic regulations

Table 4 shows that, in addition to the microbial target achieved with UV disinfection, under these experimental conditions, the upstream processes investigated (clarification and filtration) ensure that the main physico-chemical characteristics of both F and CL disinfected effluents, including boron, highly toxic for sensitive crops (Pettygrove & Asano 1985), comply with the maximum allowable concentration imposed by local agronomic regulations for *unrestricted* wastewater reuse in agriculture.

CONCLUSIONS

A 9 month pilot investigation was carried out at West Bari municipal wastewater treatment facility for a field evaluation of UV as an alternative method to chlorination for advanced disinfection of wastewater to be reused in agriculture. The experimental results referring to bacteria inactivation, obtained with three feeds of increasing quality, namely biological secondary (II), secondary-clarified (CL) and secondary-clarified-filtered (F), may be summarized as follows:

- chemical coagulation, flocculation and sedimentation followed by mechanical filtration, according to the so called 'full Title 22' treatment scheme (i.e. feed F), definitely ensured effluent characteristics properly suited for UV disinfection, achieving the stringent microbial standard for wastewater reuse in agriculture (2 CFU 100 ml^{-1} of total coliforms required by the Italian regulation, based on the well known California Wastewater Reclamation Criteria) at a dose of 100 mWs cm^{-2};
- the same standard was also affordably met by UV disinfecting just clarified secondary effluent (CL), thereby avoiding the expensive filtration step, at an increased dose of 160 mWs cm^{-2}; the excessive TSS content in feed II (average value: 21 mg l^{-1}) prevented the achievement of the target standard within the UV doses investigated ($\leq$ 430 mWs cm^{-2}), confirming suspended solids as a controlling parameter for UV disinfection performance;
- treating F and CL feeds at 100 and 160 mWs cm^{-2} respectively, UV disinfection showed extremely fast kinetics (contact time ≤20 s), yielded log-inactivation values around 5, was very effective towards resistant bacteria like *Pseudomonas aeruginosa* and ensured that all parameters of agronomic interest of both disinfected effluents complied with local regulations for wastewater reuse.

Further investigation is planned:

- to verify, with pilot plant continuous running, that the 2 CFU 100 ml^{-1} target standard achieved can be maintained as a median over a 7-day consecutive period, according to the 'full Title 22' criteria;
- to assess UV effectiveness towards other bacteria;
- to improve pilot plant operation assessing, in particular, the impact of the centrifugal feed pumps

and the homogenizer on the size characteristics of the floc.

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

Andreadakis, A., Mamais, D., Christoulas, D. & Kabylafka, S. 1999 Ultraviolet disinfection of secondary and tertiary effluent in the mediterranean region. *Wat. Sci. Technol.* **40**(4-5), 253–260.

Asano, T. 1998 *Wastewater Reclamation and Reuse*. Technomic Publishing Company, Inc., Lancaster, USA.

Awad, J., Gerba, C. & Magnuson, G. 1993 Ultraviolet disinfection for water reuse. *Proceedings of the WEF Specialty Conference Series: Planning, Design and Operation of Effluent Disinfection Systems*. Water Environ. Fed., Alexandria, VA, pp. 1–12.

Bryant, E., Fulton, G. & Budd, G. 1992 *Disinfection Alternatives for Safe Drinking Water*. Van Nostrand Reinhold, New York.

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

Chen, C., Nur, R., Stahl, J. F., Horvath, R. W. & Kuo, J. F. 1993 UV inactivation of bacteria and viruses in tertiary effluent. *Proceedings of the WEF Specialty Conference Series: Planning, Design and Operation of Effluent Disinfection Systems*. Water Environ. Fed., Alexandria, VA, pp. 61–72.

Clancy, J. L., Hargy, T. M., Marshall, M. M. & Dyksen, J. E. 1998 UV light inactivation of Cryptosporidium oocysts. *J. Am. Wat. Wks Assoc.* **90**(9), 92–102.

Emerick, R. W. & Darby, J. L. 1993 Ultraviolet light disinfection of secondary effluents: predicting performance based on water quality parameters. *Proceedings of the WEF Specialty Conference Series: Planning, Design and Operation of Effluent Disinfection Systems.* Water Environ. Fed., Alexandria, VA, pp. 187–198.

Hassen, A., Mahrouk, M., Ouzari, H., Cherif, M., Boudabous, A. & Damelincourt, J. J. 2000 UV disinfection of treated wastewater in a large-scale pilot plant and inactivation of selected bacteria in a laboratory UV device. *Bioresour. Technol.* **74,** 141–150.

Hoyer, O., Kryschi, R., Piecha, I., Mark, G., Schuchmann, M. N., Schuchmann, H-P. & von Sonntag, C. 1992 UV fluence rate determination of the low-pressure mercury arc in the UV disinfection of drinking water. *J. Wat. Suppl.: Res. & Technol.-AQUA,* **41**(2), 75–81.

IWSA (International Water Supply Association) 1997 *The Practice of Chlorination: Application, Efficacy, Problems and Alternatives*. IWSA Blue Pages. IWSA, London.

Jagger, J. 1967 *Introduction to Research in Ultraviolet Photobiology*. Prentice-Hall, Englewood Cliffs, NJ.

Karanis, P., Maier, W. A., Seitz, H. M. & Schoenen, D. 1992 UV sensitivity of protozoan parasites. *J. Wat. Suppl.: Res. & Technol.-AQUA* **41**(2), 95–100.

Liberti, L., Lopez, A. & Notarnicola, M. 1999 Disinfection with peracetic acid for domestic sewage re-use in agriculture. *J. Inst. Wat. & Environ. Managmt,* **13**(4), 262–269.

Liberti, L. & Notarnicola, M. 1999 Advanced treatment and disinfection for municipal wastewater reuse in agriculture. *Wat. Sci. Technol.* **40**(4–5), 235–245.

Liberti, L., Notarnicola, M. & Lopez, A. 2000 Advanced treatment for municipal wastewater reuse in agriculture. III—Ozone disinfection. *Ozone Sci. Engng,* **22**(2), 151–166.

Oppenheimer, J. A., Jacangelo, J. G., Lainé, J. M. & Hoagland, J. E. 1997 Testing the equivalency of ultraviolet light and chlorine for disinfection of wastewater to reclamation standards. *Wat. Environ. Res.* **69**(1), 14–24.

Pettygrove, G. S. & Asano, T. 1985 *Irrigation with Reclaimed Municipal Wastewater—A Guidance Manual*. Lewis Publishers, Chelsea, MI.

Rook, J. J. 1974 Formation of haloforms during chlorination of natural waters. *Wat. Treat. Examin.* **23,** 234–245.

Schoenen, D. 1996 The influence of inhomogeneous irradiation in UV disinfection—experimental findings and theoretical considerations. *J. Wat. Suppl.: Res. & Technol.-AQUA* **45**(3), 120–129.

Snider, K. E., Darby, J. L. & Tchobanoglous, G. 1991 *Evaluation of Ultraviolet Disinfection for Wastewater Reuse Applications in California*. Department of Civil Engineering, University of California, Davis.

Standard Methods for the Examination of Water and Wastewater 1995 19th edition, American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC.

State of California 1978 *Wastewater Reclamation Criteria*. California Administrative Code, Title 22, Division 4, California Department of Health Services, Sanitary Engineering Section, Berkeley, CA.

US-EPA 1992 *Ultraviolet Disinfection Technology Assessment*, Report EPA 832-R-92-004. Environmental Protection Agency, Washington, DC.

WEF (Water Environment Federation) 1996 Disinfecting wastewater for discharge & reuse. *Proceedings of the WEF Specialty Conference*, Portland, Oregon.

WEF 1998 Disinfection '98—The latest trends in wastewater disinfection: chlorination vs. UV disinfection. *Proceedings of the WEF Specialty Conference*, Baltimore, Maryland.

WERF (Water Environment Research Foundation) 1995 *Comparison of UV Irradiation to Chlorination: Guidance for Achieving*

Optimal UV Performance. Project 91-WWD-1 report, Water Environment Research Foundation, Alexandria, VA.

Wolfe, R. L. 1990 Ultraviolet disinfection of potable water. *Environ. Sci. Technol.*, **24**(6), 768–773.

WPCF (Water Pollution Control Federation) 1986 *Wastewater Disinfection*, Manual of Practice No. FD-10, Water Pollution Control Federation, Alexandria, VA.