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A comparative study of tertiary wastewater treatment by physico-chemical-UV process and macrofiltration–ultrafiltration technologies

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Abstract

A comparative study was undertaken of the economic costs and quality of effluents obtained from physicochemical-UV and macrofiltration–ultrafiltration as municipal wastewater tertiary treatments. A physico-chemical-UV urban wastewater treatment system was designed for the study. Pre-treatment to UV radiation disinfection consisted of coagulation with alumina (100 mg/L), sedimentation by sludge-blanket sedimentation tank (0.8 m^3/m^2 h) and filtration by sand-pressure filter (5.0 m^3/m^2 h). The ultrafiltration module was equipped with flat polyvinylidenefluoride membranes (0.05 μm pore size), with pre-treatment carried out by a sand-pressure filter (8.0 m^3/m^2 h). Both systems obtained effluent of excellent physico-chemical quality (91% removal of suspended solids and 99% turbidity removal) and microbiological quality (total absence of nematode eggs, coliforms, *E. coli* and coliphages). However, while physico-chemical quality remained constant in both systems, microbiological quality of effluent from the UV-disinfection process was shown to depend on the quality of influent, particularly with regard to transmittance. By contrast, microbiological quality remained constant in the case of membrane technology. Other control parameters such as particulate analysis confirmed the higher quality of ultrafiltration effluent in comparison with the physico-chemical-UV process. With regard to costs, both technologies present similar variable costs, while fixed costs of the membrane installation are double those of the physico-chemical-UV process, owing particularly to the high cost of the installation itself.

Keywords: Wastewater reuse; Physico-chemical treatment; UV disinfection; Sand filter; Ultrafiltration

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1. Introduction

Society's rapid evolution has increased the demand for water in every sector. At the same time, the continual production of great quantities of wastewater has led to the view that this should be considered as an alternative water resource. Nevertheless, wastewater reuse poses a risk for public health and for this reason specific levels of quality are required. Conventional treatments do not reach the minimum quality standards, since effluents from such treatments continue to present a high number of pathogenic micro-organisms [1]. Consequently, there is a need for tertiary treatments such as water disinfection technologies.

Development of new technologies has extended the possibilities of wastewater reuse [2], and this may now be applied to agriculture at all levels, as well as to irrigation of sports grounds, urban uses, industrial uses, aquifer recharge, etc. At the same time, norms regarding the quality of water to be reused have become increasingly stringent, while tertiary treatments have in turn become increasingly sophisticated as they strive to obtain effluents of high quality.

At present there are various technologies for disinfecting wastewater, capable of producing effluents of the highest microbiological quality. However, some of these treatments pose additional problems such as the presence of residual disinfectant concentrations or the formation of disinfection by-products [3]. These drawbacks limit the application of chemical disinfection technologies, with the result that there has been an increase in physical disinfection technologies, principally UV radiation and membrane technologies.

UV radiation has become established as the most commonly applied wastewater disinfection technology, with thousands of installations throughout the world. This success is owing to factors such as the efficiency of the system at eliminating viruses and bacteria, minimal presence of disinfection by-products and low cost [4]. However, one of the main problems is the resistance to UV radiation of certain microbial groups such as nematode eggs, protozoa cysts and certain viruses, which require high doses in order to be eliminated efficiently [5]. A further consideration is that the efficiency of UV radiation depends on the quality of influent. Specifically, system performance varies according to characteristics of the water such as turbidity, suspended solids concentration and transmittance [6]. Consequently, UV radiation is often linked to certain pre-treatments aimed at improving the quality of the influent, particularly with regard to particulate material content. One of the most suitable technologies in this respect is physico-chemical treatment (coagulation–sedimentation–filtration). This technology is applied in many cities throughout the world and has proved highly efficient at eliminating particulate material and at obtaining effluents which can be disinfected easily [7].

Wastewater treatment by membrane technologies has increased significantly in the last decade. In the past, these technologies were considered unsuitable owing principally to the high costs involved. However, as a result of the demand for wastewater reuse as well as the increasingly stringent norms, use of membrane technologies is now considered more viable [8]. Of the various membrane systems, microfiltration and ultrafiltration have been most extensively studied for application as wastewater disinfection treatment [4]. Both methods have proved efficient with regard to total retention of parasites and bacteria; however, only ultrafiltration retains viral particles [9]. In addition to their disinfectant capacity, membrane technologies do not present problems of resistance by target micro-organisms, while the physico-chemical quality of the water is improved since the system acts as a physical barrier to particulate material [10].

Nevertheless, membrane technologies also present certain operational drawbacks. Continual backwashing is required to avoid system clogging, as well as periodic chemical cleansing to eliminate materials which build up irreversibly in the membrane and cause fouling, which in turn affects water flow and trans-membrane pressure. These problems may be minimized by application of pre-treatments such as granular filtration [11].

All of the technologies described above obtain effluents which meet the standards established in wastewater reuse [12], and are extensively employed as wastewater tertiary treatments. The objective of the present study is to compare physico-chemical UV treatment and membrane technologies with regard to the final quality of treated effluent and the associated economic costs, with a view to establishing the applicability of each system.

2. Materials and methods

2.1. Description of pilot-scale installations

Two pilot-scale installations running in parallel were designed and built for the study (physico-chemical UV and macrofiltration–ultrafiltration). Pre-treatment to UV radiation disinfection consisted of coagulation with alumina sulphate (100 mg/L) in a coagulation–flocculation tank, sedimentation by sludge blanket (0.8 m^3/m^2 h hydraulic loading) and filtration by sand-pressure filter (0.8 mm effective size for silica sand with 5.0 m^3/m^2 h hydraulic loading). UV radiation was applied using Aquada Máxima 2 (WEDECO), a tubular model with low pressure lamps (40 W, $\lambda = 253.7$ nm) connected in series to the filtration system. The installation was designed for use with a flow-rate of 1.46 m^3/h, providing a dose of 400 J/m^2 to water with 75% transmittance. However, the dose varied according to the flow-rate applied and influent transmittance, in line with the following expression:

$$D_{\mathrm{UV}} = 400 \times \frac{0.01617T(\%) + 0.2071}{Q} \qquad (1)$$

The membrane system was a FLAMEC (FILTERPar) ultrafiltration module equipped with flat cassette-type polyvinylidenefluoride (PVDF) membranes with an average pore size of 0.05 μm. Area of filtration surface was 35 m^2, operating in a vacuum with a trans-membrane pressure of between –0.1 and –0.6 bar. Running conditions involved a 20-min production phase (1 m^3/h), followed by a 2-min backwashing (1.5 m^3/h). Alkaline chemical cleansing was carried out every 15 days (NaOH 0.3 M and NaClO at 12.5%). Acid chemical cleansing was carried out every 30 days (H_2SO_4 0.05 M), by means of recirculation for 1 h. The system was linked to a sand-pressure filter pre-treatment, filled with silica sand with an effective size of 0.8 mm and operating with a hydraulic loading of 8 m^3/m^2 h. Fig. 1 shows a scheme of the pilot-scale setup.

2.2. Experimental methodology

The comparative study was carried out using urban wastewater treated in a double-stage aerobic biological system (at the urban wastewater treatment plant in Melilla, Spain). All the systems worked continuously and samples of influent and effluent were taken daily. Total coliform, *E. coli*, total and filterable coliphages and nematode eggs were analysed as microbiological parameters. Transmittance, turbidity and suspended solids were analysed as physico-chemical parameters in all water samples.

For bacteriological and viral analyses, water samples were collected in sterile glass bottles (1 L) and analysed immediately after collection. The presence of total coliform and *E. coli* was studied using the membrane filtration procedure (UNE-EN ISO 9308-1). Coliphages were examined using a modified form of the double-agar layer method described by Adams [13], with *Escherichia coli* C (ATTC 13076) as host bacteria. Previous to analyses, 10 mL of sample or dilution was placed in a tube containing 2 mL of chloroform.

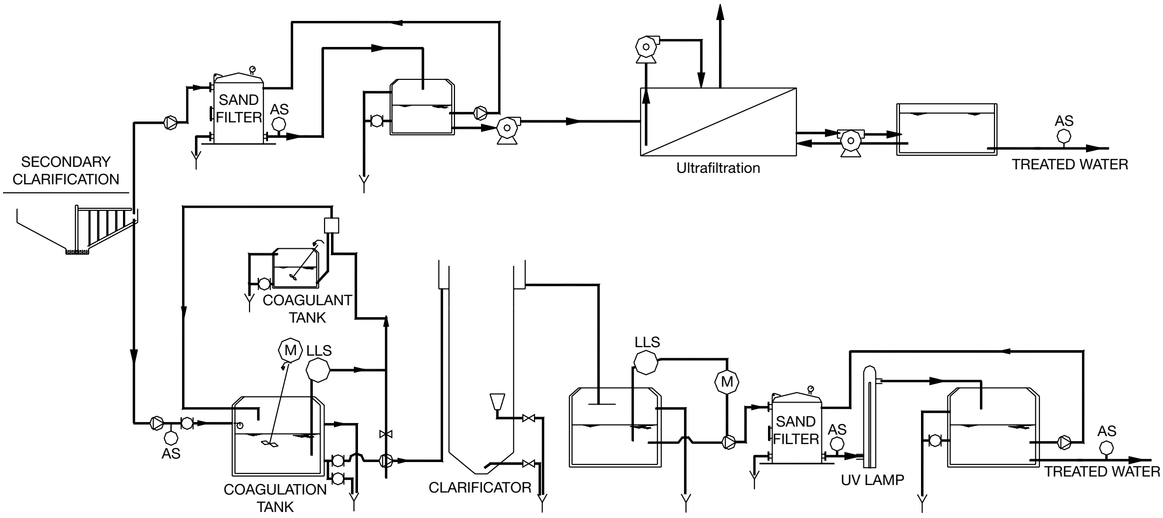

Fig. 1. Schematic diagram of experimental pilot plant.

The tube was shaken vigorously and then left to settle for 20 min; after heating at 45°C the chloroform was removed. For associated and filterable coliphage determination, samples were filtered through Millipore sterile membrane filters (0.22 μm) prior to the chloroform treatment. To determine nematode egg concentration, the modified Bailenger method was used [14]. Ten-litre samples were concentrated during 24 h of sedimentation. The count up was performed using Mc Master cameras. A spectrophotometric method at 650 nm was used to determine turbidity, while suspended solids concentration was established by a filtration method using 0.45 μm filters, as reflected in *Standard methods for the examination of water and wastewater* [15]. $UV_{253.7}$% transmittance was measured in the physico-chemical effluent by means of a HeΛios γ spectrophotometer (ThermoSpectronic). Particle analysis was carried out for each of the samples obtained, using a LiQuilaz-E20 particle counter (Particle Measuring Systems). This system employs laser light to measure by diffraction particles ranging between 2 and 125 μm in size with a resolution of 1 μm.

3. Results and discussion

3.1. Comparative analysis of water quality

As shown in Table 1, effluents from each system were similar with regard to physico-chemical characteristics (turbidity and suspended solids), with no statistically significant differences between values obtained ($p = 0.2341$). Both systems achieved considerable improvement in the quality of water, with a performance of 91% for suspended solids and 99% for turbidity. Values were maintained over time and there was no apparent correlation between influent and effluent quality.

In the macro-ultrafiltration combination, this improvement in quality was due to the sifting effect of the ultrafiltration system, while the improvement achieved by macrofiltration was less marked. Nevertheless, the quantity of particulate material retained by the sand filter makes it possible to prolong the times between backwashes and chemical cleansing phases in the ultrafiltration system, thus optimizing the process [11]. The physico-chemical UV process achieved improvement in both turbidity and suspended solids due to the physico-chemical

Table 1
Summary of sample characteristics of different effluents from analysed systems

Parameter		Treated wastewater	Physico-chemical-UV		Macrofiltration–ultrafiltration	
			Physico-chemical	UV	Sand filter	Ultrafiltration
Turbidity	NTU	4–20	0–0.5	0–0.5	1–12	0–0.9
TSS	mg/L	11–87	1–11	1–9	10–31	1–7
T-$UV_{253.7}$	%	11–41	37–76	–	–	–
Nematode eggs	Un/L	0–200	n.d.	n.d.	n.d.	n.d.
Faecal coliforms	cfu/100 mL	27000–1582000 (399870)[a]	18000–1400000 (294340)	0–1000 (130)	18000–1300000 (218000)	0–9 (1.4)
E. coli	cfu/100 mL	10000–1200000 (255300)	9000–1000000 (181500)	0–59 (6.2)	10000–1050000 (63426)	0 (0)
Total coliphage	pfu/100 mL	1000–75400 (16697)	610–46100 (9679)	0–50 (6.9)	800–49200 (12996)	0–1 (0.3)

[a] Average values.

treatment, with no apparent effect of UV disinfection on these parameters. This is consistent with the need to apply UV radiation to influents which have been clarified previously, since the presence of particulate material influences the dose of UV radiation to be applied [6].

Water transmittance was also improved by the physico-chemical process (Table 1), with influent values showing no effect on effluent values. However, the system did not achieve constant transmittance values, resulting in variations in the applied UV-radiation doses between 20 and 37 mJ/cm^2. These variations conditioned the system's capacity to inactivate micro-organisms (Table 1), with different effects on the various faecal contamination indicators analysed. *E. coli* ranged from an inactivation of 5 logarithmic units for a dose of 35 mJ/cm^2 to 2.7 logarithmic units for a dose of 26 mJ/cm^2, while faecal coliforms ranged from 6 to 1.7 logarithmic units for the same UV doses. This demonstrates the greater sensitivity of *E. coli* to UV radiation compared with faecal coliforms, as reflected in Fig. 2.

For all tested indicators, inactivation ranges (N/N_0) showed a reciprocal regression with respect to the applied dose (Table 2), reflecting the rapid loss of UV disinfection efficiency when lower doses are applied. The regressions show that total elimination of the indicators analysed ($N/N_0 = 0$) may be achieved with doses over 35 mJ/cm^2. While this is in accordance with results cited by other authors [16], the dose is insufficient to achieve total elimination of other more resistant micro-organisms, such as nematodes.

Analysis of nematode eggs revealed a total absence after treatment, due to the efficiency of both filtration and physico-chemical treatments at retaining this type of pathogen (Table 1).

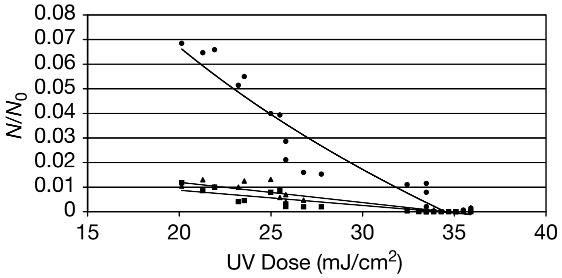

Fig. 2. Inactivation ranges according to dose of UV radiation applied for faecal coliforms (●), *E. coli* (■) and coliphages (▲). N/N_0 (effluent units/influent units).

Table 2
Results of the reciprocal regression of UV dose D (x) and inactivation rate N/N_0 (y)

Faecal indicator	r	R^2 (%)	Reciprocal regression	$N/N_0 = 0$	$N/N_0 = 1$
Faecal coliform	0.9723	94.5 1	$N/N_0 = (3.41855/D) - 0.098717$	34.64	3.11
E. coli	0.9194	84.54	$N/N_0 = (0.495142/D) - 0.014545$	34.04	0.48
Coliphages	0.9260	85.74	$N/N_0 = (0.647699/D) - 0.018614$	34.79	0.63
Filterable coliphages	0.9641	92.95	$N/N_0 = (0.11103/D) - 0.00320709$	34.6	0.11
Associated coliphages	0.9269	85.91	$N/N_0 = (0.86304/D) - 0.0249823$	34.54	0.84

Nematode eggs may thus be eliminated without the need to apply large doses of UV radiation; however, these are not the only resistant pathogens found in wastewater. Others such as *Giardia* cyst or *Crystosporidium* oocyst may also be present and may resist treatment owing to the high doses of UV radiation required for their elimination [5].

With regard to coliphages, efficiency of elimination was similar to that for *E. coli*. However, this efficiency was markedly higher for filterable coliphages than for those associated with particulate material, judging by the coefficients obtained in the reciprocal adjustments (Table 2). This underlines the effect that other parameters may have on the process, such as suspended solids concentration and turbidity.

The ultrafiltration system achieved a more stable microbiological quality, unaffected by characteristics of the water to be treated or by the type of micro-organism to be eliminated. This is due to the action mechanism of the system, based on the sifting of particulate material [10]. Of the various faecal contamination indicators analysed, only faecal coliforms posed a problem owing to their presence in the treated water. This presence is not related to influent quality or to problems with the membrane, but is principally due to contamination of the membrane in the permeate zone [17].

Analysis of particles in the secondary treatment effluent revealed a size-based distribution (2–125 μm) corresponding to a square root x-model regression ($r = -0.9797$), by which particles of lesser size predominate over larger particles (Fig. 3). This distribution varied after application of the physico-chemical treatment, resulting in a significant reduction in the number of particles, which is consistent with the considerable reduction observed in suspended solids. Size-based distribution obtained for the physico-chemical effluent also adjusts to a square root x-model regression ($r = -0.9964$), with an almost total absence of particles larger than 50 μm, explaining the absence of certain micro-organisms such as nematode eggs. With respect to small-sized particles (2 and 10 μm), a limited reduction was observed, with numbers on occasion even exceeding those recorded in the secondary

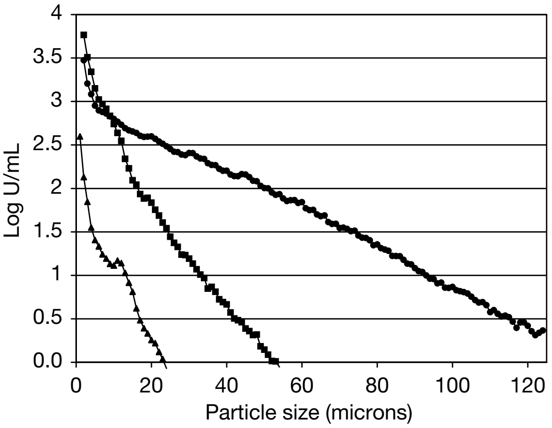

Fig. 3. Particle size distribution for secondary (●), physico-chemical-UV (■) and macrofiltration–ultrafiltration (▲) effluents.

treatment effluent. This is at odds with findings by Aguilar et al. [18], who noted a considerable reduction in particles of all sizes due following the addition of coagulant. However, use of the sand-pressure filter after the physico-chemical clarification treatment may explain the increase in the number of small particles, owing to the disintegration in the interior of the filter of flocs formed by the coagulation.

Particle distributions obtained for the ultrafiltration system also corresponded to a square root x-model regression ($r = -0.9872$), revealing a considerable decrease in the number of particles with respect to effluents from secondary and physico-chemical treatment, and presenting an almost total absence of particles larger than 25 µm. These results are consistent not only with the reduction in suspended solids concentration, but also with the retention of micro-organisms. This retention represents the principal difference between the ultrafiltration process and the physico-chemical-UV system, which only inactivated micro-organisms without eliminating them from the water. The particle analysis may therefore be said to reveal a clearly differentiating parameter with regard to the quality of water obtained from the systems assayed, in contrast to the other parameters in the study.

3.2. Costs analysis

The comparative costs analysis was based on an installation with capacity to treat 20000 m^3/d, with components similar to those described in the experimental setup scheme. Fixed and variable costs were included without taking into account corresponding taxes. It is noticeable that very similar variable costs were reached for the two systems overall, although costs for each of the items considered were different. Thus, for the physico-chemical UV system the most significant costs were reactives, representing 65% of the total variable costs. For the membrane technology, the costs of component replacement were most significant, accounting for 60% of the total variable costs, mostly due to membrane replacement. The biggest difference between the two installations lay in the fixed costs, with the cost of the membrane setup nearly doubling that of the physico-chemical UV system. Of the various items considered in the calculation of fixed costs, installation costs represents the greatest difference (Table 3).

At present, the membrane system remains less competitive than physico-chemical-UV treatment, owing particularly to the high costs of the installation and component replacement. Nevertheless, it is likely that the technology will become more competitive in the future, bearing in mind the advances achieved over the last few years, particularly with regard to membrane configuration [19] and aspects such as homogenization of membranes for ultrafiltration technology. For the present, ultrafiltration

Table 3
Comparison of fixed and variable costs in the physico-chemical UV system and macrofiltration–ultrafiltration system

	F–Q (€/m^3)	UF (€/m^3)
Total fixed costs	*0.04235*	*0.08198*
Personnel	0.00245	0.00784
Maintenance and conservation	0.00304	0.00513
General administration	0.00040	0.00114
Analysis and process control	0.00191	0.00191
Fixed energy terminals	0.00045	0.00117
Installation	0.03408	0.06480
Total variable costs	*0.03324*	*0.03319*
Reactives	0.02167	0.00476
Power	0.00516	0.00690
Component replacement	0.00205	0.01972
Retentate treatment	0.00435	0.00181
Total costs	*0.07559*	*0.11517*

membranes may be considered to offer a competitive solution in cases where it is important to obtain stable water quality, as required for example in pre-treatment for a reverse osmosis system.

4. Conclusion

Both the physico-chemical treatment combined with UV disinfection and the macrofiltration–ultrafiltration system may be considered valid types of tertiary urban wastewater treatment. The two systems obtain effluents of excellent quality with regard both to physico-chemical and microbiological aspects. However, the principal difference is that the physico-chemical-UV system does not guarantee constant stability of microbiological quality, owing principally to variations in the transmittance of the water, which are not always corrected efficiently by physico-chemical treatment. The main difference regarding the quality of effluents obtained is revealed by the particle distribution analysis, since the quality achieved by the membrane treatment is clearly superior for this parameter. Nevertheless, at present the membrane system remains less competitive than physico-chemical-UV treatment, owing particularly to the high cost of the installation and membrane replacement.

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