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Wastewater disinfection using ultraviolet (UVA, UVC) and solar radiation

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ABSTRACT

Nowadays, water availability and quality represent a major challenge. In 2050, the United Nations Organization predicts that 44% of the world population will face severe water scarcity. Countries located in sub-humid and semi-arid regions of the world will be especially concerned for this problem, because of their low supply of rainwater. The aim of this study is to suggest the disinfection treatment by irradiation as a complement wastewater treatment to obtain a safe microbial quality of water and permit its reuse. This last is limited to 1.000 CFU/100 ml (i.e. equivalent to 3 log) of fecal coliforms by the Algerian and WHO standards. The experiments were conducted to disinfect wastewater by UVA, UVC, and solar radiation. The UVA and UVC disinfection treatments were carried out using an experimental bench composed of three flat-bottom flasks and three Erlenmeyers of 2 L each. The solar disinfection treatment was experimented using a 30 L-tubular photoreactor in a stationary and a dynamic flow. The disinfection results indicate a reduction in 2.47 log of total coliforms, 3 log reduction of fecal coliforms, 2.67 log reduction of streptococci, 3.17 log reduction of staphylococci, 0.08 log reduction of yeasts, 0.19 log reduction of molds, and a reduction of 1.17 log of sulfite-spores.

Keywords: Water scarcity; Wastewater reuse; UV disinfection; Solar disinfection; Sustainable wastewater treatments

1. Introduction

In 2006, the UN estimated that 1.2 billion people did not have access to drinkable water [1]. The agricultural and economic activities are equally affected by water crisis particularly in arid areas like North Africa, Middle East, Central and Western Asia [1,2]. Water crisis affects more and more countries according to the forth report of the United Nations

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World Water Development [3]. The report predicts that in 2050 the world water demand will significantly increase. In the agriculture sector this increase will achieve by 20%.

Because of its geo-climatic position in North Africa, Algeria is inherently vulnerable. Indeed, the major part of the country is characterized by a low rainfall, between 100 and 1,000 ml/y, and high temperatures, between 25 and 45˚C during summer.

The country already experienced a water shortage at the end of the 90s and early 2000s. Facing the future increase of water needs, a new water management policy is elaborated for supplying the industrial and the agricultural sectors which consume up to 70% of water. For the agriculture, the 2010–2014 program plans the reuse of 200 million m^3 of wastewater to irrigate 40,000 ha [4].

In Algeria, the wastewater treatment sector is managed by the national sanitation office, the local authorities, the building operators, and the stock company in major cities [4]. Since, 2006, new stock companies were also formed namely: SEAAL, SEOR, and SEACO, which gather the National Office of Sanitation (ONA), the Algerian Water Company (ADE), and SUEZ Environment.

The national sanitation office manages 68 wastewater treatment plants (WWTPs) whose nominal capacity is five million PE. In 2010, 104 million m^3 of wastewater were treated out of a total collected volume of 573 million m^3 [5]. In spite of this, the sector does not treat yet all the rejected wastewater. To avoid this quantitative constraint, the increase in the wastewater treatment capacity is undertaken through the building of 40 new WWTPs which will be added to the 123 existing ones [6].

There is also a qualitative constraint; indeed, the treatment processes are still incomplete: the tertiary treatment is not applied. This situation could compromise the wastewater reuse regarding, especially the microbial quality. To secure the wastewater reuse, restrictions are adopted [7,8] and the integration of the tertiary treatment is planned.

2. Water scarcity

To evaluate water availability and predict water scarcity, several researches were performed based on per capita of water availability of renewable freshwater and the water intensity use index [9]. This last corresponds to the percentage of the consumed water, extracted from the environment (i.e. fossil groundwater), relatively to the total renewable water.

The mentioned researches allowed establishing the situation of water availability by region (Table 1). It indicates that North Africa and Middle East are the most vulnerable regions worldwide, which suffer from the lack of water. These regions are facing water shortage as water rate available is estimated as1.38 m^3/cap/y. This rate represents only 20.52% of water rate in Europe and 7.03% of the available water in North America. Consequently, the countries located in North Africa and Middle East are constraint to exploit 62.8% of the available water which is not renewable, this reduces the rate of the existing water potential for their populations. Moreover, they have to encourage seawater desalination and wastewater reuse in order to secure their water supply.

Table 1
Regional water availability and water intensity use index [9]

Region	Water availability in 2006 (m^3/cap/y)	Water intensity use index
North Africa and Middle East	1.383	62.8
Asia	3.990	19.3
Europe	6.740	6.3
United state and Canada	19.649	9.3
High income countries	10.554	10.1
Middle income countries	10.171	6.9
Low income countries	5.894	12.1
World	8.462	8.9

3. UV disinfection

UV radiation covers about 5% of the solar electromagnetic spectrum received on the earth's surface. In 1932, their spectral regions were limited between 100 and 400 nm (Copenhagen meeting of the second international congress on light held during August 1932 in [10]). But regarding their environmental and dermatological effects, now, the UV radiation is subdivided into UVA (400–320 nm) which constitutes 94%s of UV radiation. The rest is constituted by UVB (320–290 nm) and UVC (290–200 nm) [10].

UV radiation is also emitted by different types of artificial lamps as low-pressure lamps (UV: 35%, power: 1 W/cm of length arc), amalgam lamps (UV: 33%, power: 2–3 W/cm), medium-pressure lamps (UV: 10%, power density: 30 W/cm^3), electrode-less vapor lamps, ultraviolet light-emitting diodes, metal halide lamps equally xenon, excimer, and laser UV lamps, etc. [11].

UV radiation technologies are used for water disinfection because of their photobiological efficiency. The research allowed its successful application against all waterborne pathogens ([12], Zhao et al. [13]).

As compared to UVB and UVC, UVA radiation is more abundant in the solar spectrum, but induces lower photobiological effects. The wavelengths' radiations inferior to 320 nm are more active, this induces the subdivision of UVA into UVAI (400–340 nm) and UVAII (340–320 nm) [10].

Direct UV radiation use (photolysis) remains less effective, the combination of UV and semi-conductors metals (photocatalysis) as TiO_2, ZnO, Ag … records better results in water- and air-purification and in several antibacterial products (Zhao et al. [13]).

Now, several studies advised UV disinfection for its efficiency and safe use especially for wastewater treatment with the aim of its reuse [11,14–16].

4. Materials and methods

4.1. Location

The experiments were carried in the development unit of solar equipment (latitude 36,633 and longitude 2,700) located at 30 km west of Algiers, during April 2012.

4.2. Disinfection experiments

The disinfection experiments were conducted using the secondary treated wastewater recovered from Tipasa WWTP. The wastewater treatment process uses the activated sludge and sedimentation in settling ponds without any disinfection treatment.

4.3. Experimental setup

The experimental benches consist of three photoreactors of different types namely: a 2 L-flat-bottom flask, a 2 L-flat-bottom Erlenmeyer, and a 30 L-tubular photoreactor as shown in Figs. 1–3.

The two first photoreactors have been used to compare the reactors geometry under UVA, UVC, and solar radiation. The exposure duration was fixed at 60 min for UVA and UVC disinfection and at 6 h for solar radiation. The UV irradiation was carried into a lamp box composed of four lamps: 1) UVA: Phillips PL-L 24 W/10 (kmax = 365 nm) and 2) UVC: HNS/15 W/G13 (kmax = 245 nm). The reproducibility of the results was evaluated by the use of three photoreactors during each experiment.

The tubular photoreactor is a module of five glass tubes (1 m length × 65 mm interne diameter × 2 mm

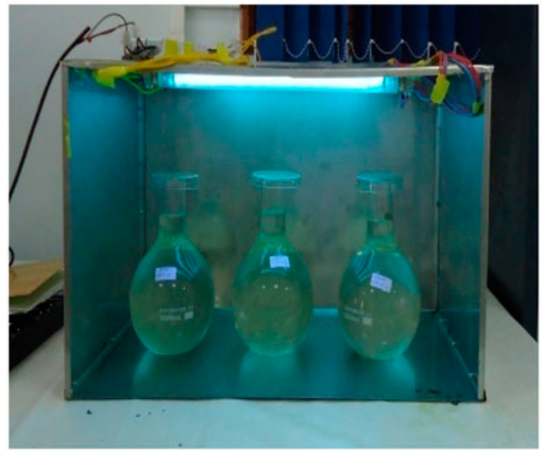

Fig. 1. 2 L-flasks under UV radiation.

Fig. 2. 2 L-Erlenmeyers under solar radiation.

Fig. 3. 30 L-tubular photoreactor under solar radiation.

thickness) assembled in series and mounted on 1 m^2-aluminum reflectors (Fig. 3). A volume of 30 L-secondary-treated wastewater was treated in closed loop with a flow of 60 l/mn using a re-cycling pump.

The photoreactor was tested to compare the effect of the flow regime and the solar exposure duration fixed at 4, 5, and 6 h.

All the experiments conducted under solar radiation were carried out from 9 am to 3 pm.

4.4. Solar radiation measurement

During the solar exposure, the incident solar radiation was systematically measured each 5 min by a radiometer brand KIPP and ZONEN, CPM 11. To compare the disinfection efficiency results under different solar radiation, a cumulative solar UV dose was calculated as follow:

$$\text{Dose UV} = \int_{t_1}^{t_2} I_{UV} \cdot \mathrm{d}t \qquad (1)$$

where I_{uv}: incident solar UV radiation (W/m^2) and t: time (s)

The UV radiation was estimated at 5% of the global solar radiation. This percentage is indicated in the literature [10] and recorded in the southern Spain and characterized by nearly similar conditions (i.e. geographic and climatic) to those of northern part of Algeria [17,18].

4.5. Microbiologic analysis

The UV disinfection efficiency was evaluated by the enumeration of the living pathogenic colonies after each experiment. The most probable number method was followed to enumerate total and fecal coliforms, streptococci, staphylococci, sulfite-reducing spores, and fungi.

The samples were filtered through 0.45 μm then seeded in selective culture media during 48 h. The number of micro-organisms was plotted as CFU/100 ml and the disinfection result was plotted in log reduction as follows:

$$\text{Log reduction} = \text{Log}\frac{C_0}{C} \qquad (2)$$

where C_0: number of surviving pathogenic before treatment and C: number of surviving pathogenic after treatment.

5. Results

5.1. The secondary-treated wastewater characteristics

During the experimentation period (i.e. April 2012), the physical and chemical characteristics of the secondary-treated wastewater was analyzed in the WWTP laboratory. The average results (Table 2) indicate that the treated water quality was in conformity to the Algerian and WHO standards of rejected wastewater.

This is not the case for the microbiological characteristics which do not allow the wastewater reuse for agriculture, because of the fecal coliforms presence with a rate that exceeds the threshold authorized by the Algerian and WHO standards [7,8] fixed at 3 log.

It is considered as a contamination indicator.

5.2. Artificial UV disinfection using 2 L-photoreactors

The disinfection results are expressed relatively to a detection limit of 0.3 log (i.e. 2 CFU/ml). During 1 h

Table 2
Physical, chemical, and microbial characteristics of treated wastewater

Physical and chemical characteristics		Microbiological characteristics	
		Bacteria	Log (CFU/100 ml)
Temperature (˚C)	19.8	Total coliforms	3.47
pH	7.9	Fecal coliforms	3.18
Conductivity (μS/cm)	1,609	Staphylococci	3.02
TSS (mg/l)	12.9	Streptococci	2.95
BOD (mg/l)	2.8	Sulphite-reducing spores	2.66
COD (mg/l)	28.3	Yeasts	2.24
NO_3 (mg/l)	14.1	Molds	1.80
NH_4 (mg/l)	2		
P (mg/l)	0.9		

Note: TSS: total suspended solids; BDO_5: biochemical oxygen demand measured after five days; CDO: chemical oxygen demand; CFU: colony-forming unit.

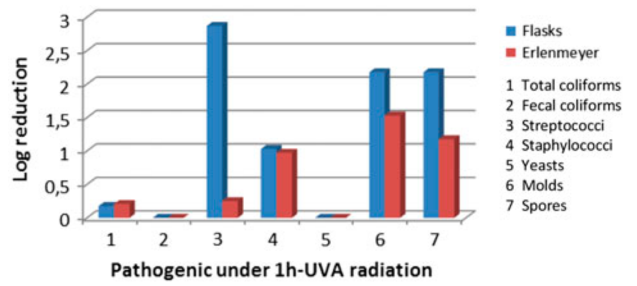

Fig. 4. Secondary-treated wastewater disinfected by 1 h-UVA irradiation.

exposure, the cumulative dose of UVA radiation was estimated at 96 and 60 Wh for the UVC radiation.

In a general trend, the UV disinfection showed a small disparity relating to the photoreactors geometry. It could be noticed that the 2 L-flat-bottom flasks recorded better results than the 2-L Erlenmeyers under both UVA and UVC irradiation (see Figs. 4 and 5). The single exception is the significant disinfection disparity recorded for the streptococci after the UVA irradiation using the 2 L-flat-bottom flasks as compared to the Erlenmeyers (Fig. 4). This should be considered as a microbiologic analysis error.

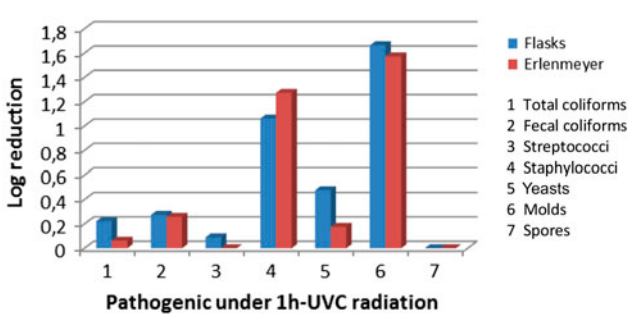

Fig. 5. Secondary-treated wastewater disinfected by 1 h-UVC radiation.

Regarding the type of UV radiation, the results have not showed the efficiency improvement of the pathogenic disinfection undoubtedly, because of the low exposure duration (i.e. 1 h). In spite of this, the results were in accordance with the literature because UVC radiation, recognized as germicide, was more efficient than UVA radiation except for molds disinfection. Their inactivation ranged from 1.5 log reduction to 2.17 log reduction using UVA radiation as compared with the UVC irradiation which induced ~1.6 log reduction of molds.

Referring to fecal coliforms, considered as a microbial quality parameter, their inactivation had been evaluated at ~0.2 log reduction using UVC radiation. But UVA irradiation did not succeed to inactivate them.

5.3. Solar disinfection using 2 L-photoreactors

The solar disinfection had been characterized by a cumulative UV radiation 1.27 kWh/m^2 obtained during 6 h (i.e. from 9 am to 3 pm).

No disparity relating to the photoreactors geometry was founded except for yeasts. Comparatively to the artificial UV radiation, the solar disinfection was widely more efficient. However, it is to notice that the pathogen concentration of the witness sample was low as compared with that recorded during the artificial UV disinfection (Table 3).

Fig. 6 shows that the most significant results have been recorded by fecal coliforms. The disinfection was estimated at 2.36 log reduction against 0.25 log reduction obtained by the UVC radiation use (cf. Fig. 5). A better elimination of the rest of pathogenic was recorded. On the contrary, molds recorded a near-similar reduction as compared with the UVC radiation (i.e. 1.77 log reduction against 1.60 log reduction). It is to notice that, during these experiments, the disinfection results of total coliforms and yeasts could not be analyzed.

Table 3
Initial pathogen concentration of witness samples in log (CFU/100 ml)

Photoreactor	Radiation	Total coliforms	Fecal coliforms	Streptococci	Staphylococci	Yeasts	Molds	Spores
Flask and Erlenmeyer	UVA and UVC	3.477	2.973	2.806	3.477	1.778	1.778	3.176
Flask and Erlenmeyer	Solar	–	2.361	2.301	2.698	–	1.778	1.845
Tubular	Solar	3.477	2.662	2.602	3	2.176	2.079	2.544
Tubular	Solar	3.477	3.176	2.672	3.176	1.477	1.477	2.477

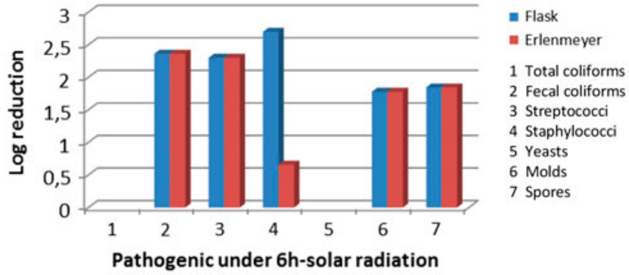

Fig. 6. Secondary-treated wastewater disinfection by 6 h-solar radiations.

In evidence, the improvement of the disinfection results was achieved by the increase in the cumulative UV radiation.

The wastewater heating induced by the solar radiation is also a second parameter of the disinfection performance. Indeed, several studies indicated that the combined use of both solar radiation and water heating improve the disinfection [19,20]. However, during the experiments, the heating temperature had not exceeded 35˚C. This temperature is not considered as significant for solar water disinfection [20]. Effectively, a heating at 50˚C was considered as being optimal for a complete disinfection from fecal coliforms during 6 h solar exposure which cumulated 180.68 Wh/m^2 of UV radiation [21]. This temperature is also recommended for drinking water disinfection using solar radiation [20].

5.4. Solar disinfection using a 30 L-tubular photoreactor

During the solar exposure of 6 h, a solar UV radiation of 0.78 kWh/m^2 had been accumulated.

Fig. 7 shows that, except the total coliforms, an improvement in the microbiological quality of the secondary-treated wastewater was recorded using the static 30 L-tubular photoreactor. To compare with

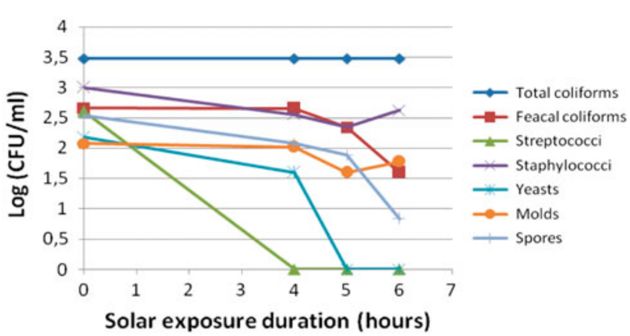

Fig. 7. Temporal secondary-treated wastewater disinfection using a static 30 L-tubular photoreactor under solar radiation.

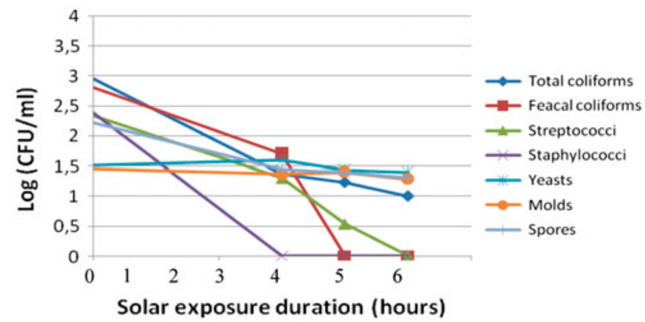

Fig. 8. Temporal secondary-treated wastewater disinfection using a dynamic 30 L-tubular photoreactor under solar radiation.

UVC radiation, the most significant disinfection had been recorded for the fecal coliforms with 2 log reduction, sulfite-spores with 2.5 log reduction, yeasts with 2.15 log reduction, and molds with 0.4 log reduction.

An important part of UV radiation was accumulated after 6 h of solar exposure, it was estimated at 1.48 kWh/m^2. This radiation energy and the use of the 30 L-tubular photoreactor with a flow of 60 l/min allowed a better bacteria inactivation.

The improvement of the disinfection efficiency had been evident (see Fig. 8) especially for total coliforms with an increase in 2.47 log reduction, fecal coliforms with 1.9 log reduction, and staphylococci with 2.75 log reduction. Streptococci recorded the slightest increase estimated at 0.05 log reduction. On the contrary, the disinfection was less efficient regarding yeasts and molds.

6. Conclusion

In Algeria, wastewater is mainly treated by the activated sludge process without disinfection. According to the Algerian and WHO standards, the treated wastewater should not be reused, because its microbial quality does not meet the standards so it threatens the public health.

The study suggested that the UV disinfection generated from artificial source and natural sunlight, because of their efficiency and safe use as compared to the chlorination.

The artificial UV radiation recorded a slight improvement of the secondary-treated wastewater microbial quality. Undoubtedly, this result was induced by the low-exposure time, fixed at 1 h, which allowed the accumulation of 96 Wh of UVA and 60 Wh of UVC radiation. The experiments showed an insignificant disinfection results during the comparative use between 2 L-flat-bottom flasks and

2 L-Erlenmeyers flask. But the results of UV irradiation had indicated that UVC radiation had been slightly more efficient than the UVA radiation.

During the exposure to solar radiation, a cumulative dose of 1.27 Wh/m^2 was surely at the origin of the better results. The experiment recorded 2.36 log reduction of fecal coliforms and streptococci against, respectively, 0.25 log reduction 0.05 log reduction after the UVC irradiation.

The solar disinfection of the secondary treated wastewater using the 30 L-tubular photoreactor, conducted in a closed loop with a flow rate of 60 l/min, had been improved. This could be induced by the solar radiation increase which passed from 0.78 to 1.48 Wh/m^2. Comparatively with the static photoreactor, the disinfection results recorded an increase regarding total coliforms with 2.47 log reduction, fecal coliforms with 1.9 log reduction, and staphylococci with 2.79 log reduction. In the opposite, the disinfection of yeasts, molds, and spores recorded decreases.

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