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Ozonation of wastewater for irrigation in a plant powered by photovoltaic energy

Mokhtaria Jbilou[1], Said Nemmich[2], Kamel Nassour[1], Mohamed Nadjib Brahami[1], Mohamed Bouhmama[2], Mostafa Bahami[1], Amar Tilmatine[2,*]

[1] ICEPS Laboratory, Djillali Liabes University of Sidi-Bel-Abbes, Algeria
[2] APELEC Laboratory, Djillali Liabes University of Sidi-Bel-Abbes, Algeria

* Corresponding author: amar.tilmatine@univ-sba.dz (Amar Tilmatine)

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Abstract

In Algeria and many other developing countries, the reuse of effluents from urban wastewater treatment plants for irrigation is prohibited because the bacterial and heavy metal load in such wastewater exceeds the maximum permissible limit. The aim of this study was to demonstrate the feasibility of using an ozone water treatment system powered by photovoltaic electrical energy for irrigation in agriculture. In this study, effluents treated by the wastewater treatment plant of Sidi-Bel-Abbes city were investigated. Bacteriological and physicochemical analyses of the ozone-treated wastewater were performed before and after ozone treatment. Analysis of heavy metals, pH, temperature, biological oxygen demand, chemical oxygen demand, suspended matter, and microbial activity (bacteria, viruses, and parasites) revealed that the levels of all parameters were lower than the national and international irrigation standards.

Keywords: Ozone water treatment, voltage waveform, energy efficiency.

1. Introduction

In developing countries, wastewater is generally discharged after limited or no treatment into natural water bodies, leading to pollution of the water bodies [1−2]. Farmers in urban areas of such countries use wastewater for irrigation [3-4], and this practice is prevalent especially in countries where climate variability and extreme weather conditions negatively influence the socioeconomic development and cause droughts [5−6]. In some regions, farmers have been deliberately using undiluted wastewater because of its low cost [7]. This practice is a hazard to both human health and environment [8−9] because undiluted wastewater contains pathogens, heavy metals, and other unwanted constituents. Farmers in many countries are not fully aware of the potential effects of wastewater irrigation [10−11].

Ozone (O_3) is an unstable and colourless gas. It is also a powerful oxidiser and a potent germicide. Moreover, it possesses a considerably higher disinfection potential than chlorine and other disinfectants. Currently, ozone is typically used as a disinfecting and oxidising agent and a substitute for chlorine because chlorine presents inherent problems of unpleasant odour and taste and generation of carcinogenic agents resulting from its use. Ozone is used for disinfection, bleaching, water and air purification, chemistry, and in pharmaceutical applications [12].

Ozone treatment of wastewater could be an economic solution that can improve the physicochemical and bacteriological characteristics of wastewater for possible reuse in agriculture [13−14]. This ozone treatment can be combined with ceramic membrane filtration to improve membrane flow performance during water treatment [15]. Although numerous studies have been conducted to analyse the effectiveness of ozone in wastewater treatment [16–19], only a few studies have focused on ozonation as a complementary solution for the reuse of treated water for agricultural purposes [20–22].

Although ozone technology has been applied for many years for the treatment of drinking water, its application for the treatment of municipal wastewater has begun recently. Ozone technology remains an effective means for the removal of several compounds, such as active pharmaceuticals, heavy metals, and bacteria [22]. Ozone can be used to disinfect a primary effluent from a municipal wastewater treatment plant and preserve the nutrient levels (in particular, nitrogen and phosphorus) of wastewater for possible reuse in agriculture simultaneously [23−24].

Connecting to conventional electrical energy remains a serious problem in isolated sites. Electrification by photovoltaic (PV) solar energy is an alternative solution for housing on an isolated site, far from the electrical grid. The PV system advantages include a long service life, reduced maintenance, ease of installation and no fuel consumption. The high cost of the investments needed to expand public networks as well as the limited needs of the remote areas concerned will continue to hinder their connection in the medium term. This is why PV systems are nowadays widely used in isolated sites [25].

The objective of this study was to investigate the feasibility of treating wastewater from the Sidi-Bel-Abbes (Algeria) purification station with ozone to ensure the reuse of wastewater in agriculture as well as the autonomous supply of electricity by photovoltaic energy. In addition, physicochemical and bacteriological analyses of ozone-treated wastewater were performed to determine the effectiveness of the device used. In our study, Algerian standards supported by WHO standards were used [2].

2. Materials and methods

2.1 Municipal wastewater treatment plant

The municipal wastewater treatment plant (WWTP) of Sidi-Bel-Abbes, Algeria, is located in the northeast of the city. In the first phase, WWTP is to be connected to 220,000 homes, and in the second phase, it is expected to reach 330,000 homes. The WWTP can treat a volume of 28,000 m^3 per day of wastewater from various discharges of the city. The flow to be discharged in the event of rains is of the order of 2920 $m^3\ h^{-1}$, with a peak flow over 14 h of 2000 $m^3\ h^{-1}$ [26].

This station is intended to purify domestic or industrial wastewater and rainwater before it is discharged into the ‘Oued-Mekerra River’, which crosses several agricultural lands. The treatment reduces the organic and solid load in suspension and removes toxic chemical constituents of the wastewater and biological constituents that are considered hazardous for public health. Tables 1 and 2 summarise the results of the physicochemical and microbial analyses of water entering and leaving the WWTP. The results of the analyses revealed that plant treatment can improve the quality of wastewater in accordance with the Algerian standards related to the protection of aquatic environments [27]. However, discharges from the wastewater treatment plant do not comply with the standards for water for irrigation, according to Algerian regulations [28].

The glass tube of 2.5 mm thickness, acting as a dielectric barrier, is 250 mm length and has an inner diameter of 48 mm. The grounded cylindrical electrode is a stainless steel tube of 220 mm length and 50 mm inner diameter. We opted thus for a discharge gap of 1 mm, which is the value often used for this type of ozone generator [29].

2.2 Experimental setup

The experimental setup included a photovoltaic (PV) generator and an ozone water treatment system.

PV system:

A solar PV generator including the supporting structure is displayed in Fig. 1. This equipment was used for ozone water treatment by using solar energy in a rural area with no access to the grid. Fig. 2 illustrates the autonomous system under study. The battery was used to store electrical energy. This solar energy system included a PV generator producing a power of 340 W (4 panels of 85 Wp each (Watt peak, the maximum electrical power that can be supplied by a photovoltaic panel), a regulator (2) (12/24 V, 20 A, loaded 13.7/13.1 V unloaded 11.8/12.6 V) to maintain the voltage of the panel at 12 V, and a solar battery (3) of 80 Ah to store the energy. The inverter (4) (10.5–15 V, 750 W) was used to convert the voltage from DC to AC. In this study, the tilt and orientation were motorised and remote controlled.

The solar PV generator consisted of a mechanical part that included an aluminium frame for adjusting the panels [30]. A DC motor was used to adjust this mechanical arm to balance and lift the frame of the PV panels by hinges a horizontal axis, which undergoes a rotational movement.

Two pulleys and belts were used to transfer the motion of the motor shaft to the axis support. A cylinder driven by a DC motor, coupled to a rotary/linear motion transformation system, was used to adjust the orientation of the panel on various vertical positions. A tubular metal support with a four-foot base ensured the seating and stability of the prototype [30, 31].

Ozone water treatment system:

As depicted in Fig. 2, first, untreated water was pumped from reservoir (9) towards reservoir (11) by opening valves 7 and 8. When reservoir 11 was totally filled, valves 7 and 8 were closed, and water was allowed to circulate in a closed loop between the two reservoirs. Untreated water was pumped from reservoir 11, passed through the Venturi injector, and ozonated water was then reintroduced in reservoir 11. Ozone was produced by a self-developed ozone generator that transforms oxygen (O_2) to ozone (O_3).

Ozone generators such as dielectric barrier discharge (DBD) reactors are used for water treatment and air disinfection. Fig. 3 illustrates DBD ozone generator used in this study. The inner cylindrical high-voltage electrode was an adhesive aluminium sheath inserted in a glass tube with a closed contact of their surfaces. The glass tube with a thickness of 2.5 mm, functioning as a dielectric barrier, was 300-mm long and had an outer diameter of 50 mm. The grounded cylindrical electrode was a 250-mm long stainless steel tube [29].

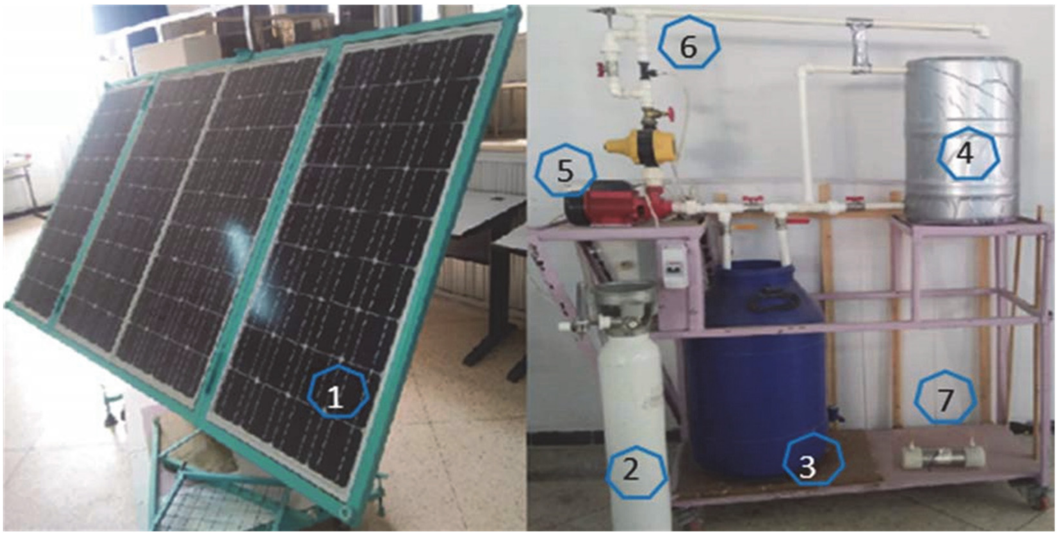

Fig. 1. Experimental setup: 1) PVG, 2) oxygen tank, 3) pent, 4) reservoir, 5) pump, 6) O_3 injector, and 7) O_3 generator.

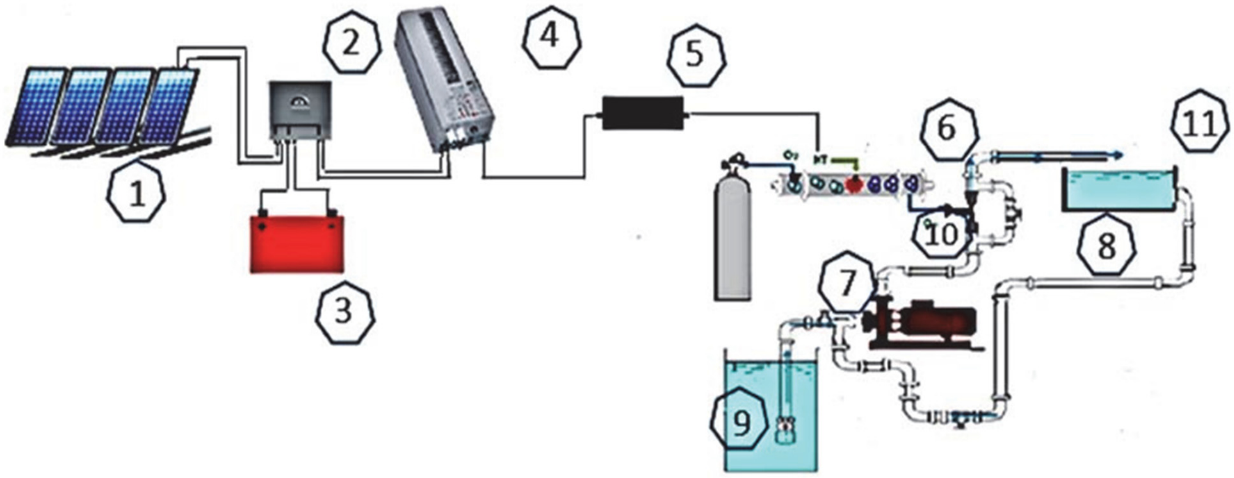

Fig. 2. Schematic of the water treatment system: (1) solar panel, (2) load regulator, (3) battery, (4) DC-AC converter (inverter), (5) HV transformer, (6) ozone generator, (7,8) valves, (9) untreated water reservoir, (10) venturi injector, (11) treated water reservoir.

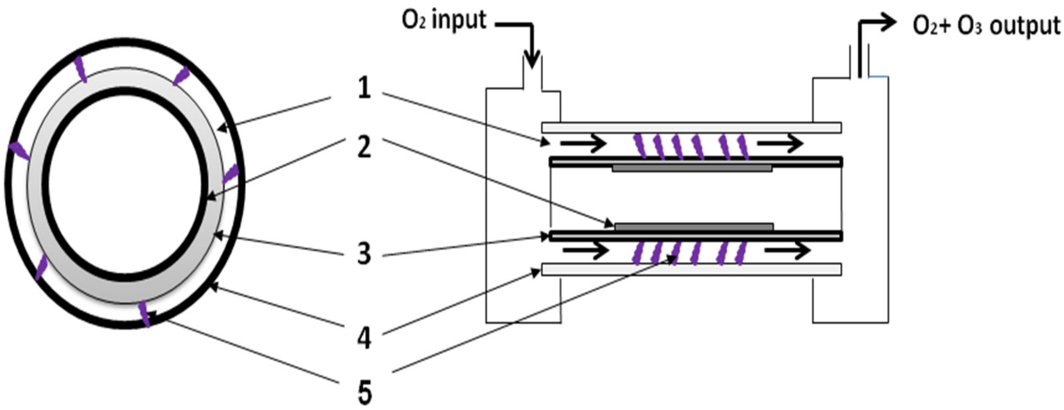

Fig. 3. Volume dielectric barrier discharge reactor: 1. discharge gap, 2. high-voltage electrode, 3. glass tube, 4. grounded electrode, 5. plasma.

2.3 Chemical and bacteriological analyses

Measurements of treated purified water samples were performed through conventional methods. The pH was measured using a PH metre (Hanna, PH 211), and conductivity and turbidity were measured using a conductivity meter (HACH) and a turbidimeter (LOVIBOND-PCH 73394), respectively. Dissolved oxygen was measured using a benchtop oximeter (Hanna, HI9146). A filtration device, filter paper, oven, and balance were used to obtain suspended matter, which was dried at 105 °C and then weighed. The COD measurement was performed using a blank prepared by mixing distilled water with a potassium dichromate ($K_2Cr_2O_7$) digestive solution tablet of 0 to 150 ppm for the treated water. After a reaction time of 2 h in the thermoreactor at 150 °C and cooling for 20 min, a calibrated spectrophotometer was used for measurements.

The determination of the biochemical oxygen demand after 5 days (BOD5) is carried out according to the method with OxiTop, based on a measurement of the pressure in a closed system. The measured water sample is introduced into amber flasks kept in a BOD chamber and incubated in the presence of air at a temperature of 20 ° C for 5 days. the microorganisms that are found consume oxygen forming carbon dioxide CO_2 which is trapped by the introduction of the sodium hydroxide (NaOH) reagent. Each bottle is fitted with a Velp Scientifica type manometer which records the depression caused by the consumption of O_2.

The concentration of phosphorus (PO_4^{3-}) (reagent: Phosver3 Reagent), nitrates (NO_3^-) (reagent: Permachem Reagent Nitraver5), nitrites (NO_2^-) (reagent: Nitriver3 Reagent), and ammonium ions (NH_4^+) (reagents: MINIRAL STABILISER, Polyvenyl Alcohol and Nestler Reagent) was determined using a colorimetric assay and a DR3900-type spectrophotometer. Sulphates (SO_4^{2-}) were examined using a UV spectrometer.

The contents of heavy metals (Zn, Cd, Cu, Fe, and Br) were determined by applying a relevant analysis method. The samples, immediately after their arrival at the laboratory, were acidified to pH 2.5 with 5N HCl and vacuum filtered through filtration membranes having a porosity of 0.45 µm by using an SAA atomic absorption spectrophotometer.

Bacteria identification was performed using the conventional most probable number method [32]. Fecal coliforms were identified using the liquid seeding technique, with incubation at 37 °C for 24–48 h, introduction of Schubert's medium, and incubation at 44 °C for 24 h. The appearance of a cloudy environment and the evolution of gas confirmed the presence of fecal coliforms. Under similar conditions, the presence of E. coli was confirmed based on the effect of Kovac's reagent and appearance of a red ring on the surface. Fecal streptococci detection was performed in the Rothe and Eva Litsky media, with incubation at 37 °C for 24–48 h. In Rothe's medium, the presence of fecal streptococci was identified by the appearance of a microbial disorder and the formation of a purple pellet at the bottom of the tube of the Eva Litsky medium. Sulfite-reducing clostridium was examined using the meat-liver agar incorporation method. After incubation for 24 and 48 h at 37 °C, black colonies of sulfite-reducing clostridium were observed.

3. Results and discussion

A series of analyses were performed on untreated and treated water to evaluate the effect of ozone treatment and to optimise the effectiveness of the treatment. The objective was to obtain water of acceptable standards that can be used for irrigation. Results of the physicochemical and bacteriological analyses before and after treatment of the water with ozone are presented in Tables 1 and 2, respectively; the values for irrigation water as per the Algerian standards are also presented in the tables.

Table 1. Results of physicochemical analyses.

Parameter	Units	Wastewater (WW)	Treated Wastewater (TWW)	Ozone-treated wastewater (OTWW)	Irrigation Limit values
PH	–	9	9.10	7.66	6-9.5
T	°C	25.02	24	23.90	30
TSM (Total suspended mater)	mg L^{-1}	219	18	0	30
Turbidity NTU	–	187	46	2.3	10
Elect.cond	µS m^{-1}	3900	2600	1900	3000
SAR (Sodium Adsorption Ratio)	meq L^{-1}		6.78	3.13	<6
COD	MgO_2 L^{-1}	460	68	22	90
BOD	mgO_2 L^{-1}	515	38	20	30
O_2Dissous	mg L^{-1}	2.12	6.98	5	<5
Phosfate PO_4^-	mg L^{-1}	1.50	1.39	0.90	5
Fe^{+2}	mg L^{-1}	Traces	Traces	0	20
Copper Cu^{2+}	mg L^{-1}	0.20	0.10	0.05	3
Zinc Zn^{2+}	mg L^{-1}	0.13	0.02	0.001	5
Bore	mg L^{-1}	0.05	0.02	0.02	2
Sulphate SO_4^{2-}	mg L^{-1}	310	9.10	0.20	250
Amonium NH_4^+	mg L^{-1}	0.621	2.48	0.28	0.50
Nitrates NO_3^-	mg L^{-1}	0.23	1.12	0.22	5
Nitrites NO_2^-	mg L^{-1}	0.14	0.557	0.71	3

Table 2. Results of bacteriological analyses.

Parameter	Units	Wastewater (WW)	Treated Wastewater (TWW)	Ozone-treated wastewater (OTWW)	Irrigation limit values
Fecal colifrm	UFC/100 mL	310×10^5	250	8	3.5×10^2
Total coliform	UFC/100 mL	322×10^5	270	15	10
Fecal,st/100 mL	–	200×10^4	1020	12	-
TSt/100 mL	–	200×10^5	5.67	2	-
Chlostridium mL^{-1}	–	30	28	10	-
Salmonella mL^{-1}	–	232×10^4	0	0	Absence in 5 L
Vibrio-cholerae mL^{-1}	–	100×10^4	0	0	Absence in 450 mL
E. coli	UFC/100 mL	36×10^5	100×10^4	0	100

3.1 Physical analysis

Hydrogen potential:

The hydrogen potential (pH) of water influences the solubility of mineral salts. Undissolved minerals are not absorbed by plants because plants can absorb only minerals, such as ions, from aqueous solutions or directly from water or soil solution [33]. Water with a pH level between 6 and 9.5 is most conducive for plants. Acidification of water results in a risk of degradation of the soil structure, a decrease in biological activities, and an increased risk of induced toxicity. Therefore, the pH of the water used for irrigation should be between 6.5 and 9.5 (irrigation limit) [28]. The evolution of the pH after ozonation treatment is displayed in Table 1. The ozone treatment reduced the pH by 15.8% (i.e. from 9.1 to 7.66).

Effect on suspended matter:

Suspended matter in irrigation water accumulates on the surface of the soil and reduce its porosity [33-34]. Drying of soil results in the formation of a battance crust. Consequently, the infiltration of water decreases, which influences the growth of vegetation. The ozone treatment of the water resulted in the complete removal of all suspended solids, which demonstrated the effectiveness of ozone treatment.

Effect on turbidity:

Turbidity is the degree of clarity of water and is quantified by interference with the passage of light through soluble organic compounds and suspended solids [33]. This parameter provides an indirect indication of the presence of microorganisms [34]. Among the water quality parameters measured in this study in conjunction with the effect of ozonation, turbidity reduction was the highest (Table 1). Ozonation eliminated nearly 95% of the turbidity, with a decrease from 46 to 2.3 NTU. The turbidity removal process was highly active at the start of testing, with more than half of the reduction occurring within the first 40 min of treatment (approximately 92.9%). Subsequently, the turbidity improved slightly until it reached equilibrium with a percentage ranging from 93.6% to 95%. This sharp increase was attributed to the rapid reaction of turbidity with molecular ozone. The results revealed a high efficiency and a considerable reduction in turbidity well below the Algerian standards for irrigation [28].

Electrical conductivity:

The concentrations of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), chlorides (Cl^{-}), sulphates (SO_4^{2-}), and bicarbonates (HCO_3^{-}) determine the salinity of water. High salinity indicates the presence of numerous ions in the solution, which renders the absorption of water and minerals by plants difficult. High salinity can cause root burns [35]. Conductivity, which indicates the ability of an aqueous solution to conduct electric current, is a critical parameter for controlling the quality of irrigation water. Conductivity is naturally influenced by the pH and valence of the ions and their degree of ionisation. Typically, water with conductivity up to 750 µS cm^{-1} is considered to be of good quality. From 750 to 2000 µS cm^{-1}, the influence of the ionic composition and nature of the salt plays a critical role in the choice of irrigation water. Water with conductivity > 3000 µS cm^{-1} has excessive salinity and cannot be used for irrigation. The ozonation of the wastewater reduced the conductivity value from 2600 to 1900 µS cm^{-1}, which is well below the irrigation limit value of 3000 µS cm^{-1}.

Sodium adsorption ratio:

Sodicity of water and soil is typically determined using the sodium adsorption rate (SAR). The SAR defines sodicity in terms of the ratio of the relative concentration of sodium (Na) to the sum of calcium (Ca) and magnesium (Mg) ions in a sample. The SAR assesses the potential for seepage problems due to sodium imbalance in irrigation water. The SAR is defined using the following mathematical formula (1):

$$SAR = \frac{Na^{+}}{\sqrt{\frac{(Ca^{2+}) + (Mg^{2+})}{2}}} \tag{1}$$

Na^{+}: Sodium ion in irrigation water reported in mill equivalents per liter
Ca^{2+}: Calcium ion, expressed in mill equivalents per liter
Mg^{2+}: Magnesium ion in irrigation water reported in mill equivalents per liter
The concentrations of these ions in water samples are typically reported in milligrams per liter (mg L^{-1})
meq L^{-1} = mg L^{-1} divided by the atomic weight of the ion divided by the ionic charge
(Na^{+} = 23.0 mg meq^{-1}, Ca^{2+} = 20.0 mg meq^{-1}, Mg^{2+} = 12.15 mg meq^{-1})
Water with a SAR between 0 and 6 can generally be used on any type of soil. When the SAR is between 6 and 9, the chances of soil permeability increase. The SAR of ozone-treated water decreased from 6.78 to 3.13 with a reduction of 53.83%, which revealed the considerable effect of ozone on sodicity [36].

3.2 Chemical analysis

Effect of treatment on COD and BOD5:
COD is an excellent indicator of the amount of chemically oxidisable organic substances present in water [36]. In this study, the COD concentration was analyzed to assess the removal of pollutants reacting with ozone. Studies have revealed a strong reduction of COD during ozonation [16]. Ozone treatment revealed a COD reduction of 67.7% from 68 to 22 because of the degradation of cyclic compounds and aliphatic compounds. Although the two values indicated before and after ozone treatment were both lower than the standards for irrigation water (90 mg L^{-1}) [27], the effectiveness of ozone treatment was confirmed. The treated wastewater satisfied WHO standards [37].

BOD5 is the concentration of dissolved oxygen consumed by microorganisms to oxidize organic substances, dissolved, or in suspension [36]. The improvement in the biodegradability of wastewater induced by ozonation has been reported in numerous studies [20−38]. The BOD5 concentration values varied by 47.36% from 38 to 20 mg L^{-1} (Table 1). The biodegradable organic matter load after ozonation was attributed to the abundance of the bacterial population responsible for this elimination and to the decrease in the oxygen content due to its consumption by microorganisms [38]. These results revealed the increase in the biodegradability of organic matter, with a residual concentration of BOD5 (20 mg L^{-1}) in accordance with Algerian standards (30 mg L^{-1}) [33], WHO standards (30 mg L^{-1}) [37], and extreme standards of irrigation water (30 mg L^{-1}) [14].
Biodegradability:

Biodegradability is expressed as K = COD/BOD5, and it is used as an indication of the biological treatability of organic materials [22]. Ozonation reduced the K ratio from 1.8 to 1.1. These observations indicated that the ozonation of organic matter resulted in the transformation of compounds of greater relative molecular mass into smaller, more biodegradable compounds.

3.3 Toxic elements

Removal of heavy metals:

The substances for analysis were selected according to their presence in wastewater [32–34], physicochemical properties (mainly non-biodegradable and hydrophilic substances), toxicity, and regulation. Their limit of quantification as well as the availability of a reliable analytical method were also considered. Studies on the treatment of micro pollutants in wastewater were considered. In this study, we considered the following elements: Cd, Cu, Fe, Zn, and Br, which are the most studied heavy metals in surface waters. Even at low concentrations, the ecological and health effects of these metals are considerable.

Analysis of the treated wastewater at the outlet of the treatment plant revealed the absence of Cd (Table 1) and the presence of Fe, Zn, Cu, and Br.

The data revealed that ozonation provides excellent results because some inorganic substances were highly oxidized. Table 1 summarizes the main results obtained in terms of micropollutant removal efficiency compared with conventional treatment (primary and secondary) of domestic wastewater (> 80%). The effectiveness of these processes for the elimination of different classes of micropollutants in the effluents discharged by the municipal wastewater treatment plant has been demonstrated [6, 39–40]. According to the present study, the ozone process appears to be a competitive solution because iron, zinc, copper, and sulfate were oxidized in treated water with low organic content. For boron, no appreciable formation of bromate or bromoform was observed after ozonation of purified water. Thus, the level of bromoform already present in the form of a trace (0.02) remained constant during the ozonation process. These results can be explained by considering the following reactions potentially occurring during the ozonation of waters containing bromide ions [31]:

$$O_3 + Br^- = O_2 + BrO^- \tag{2}$$

$$2O_3 + BrO^- = 2O_2 + BrO_3^- \tag{3}$$

$$H^+ + BrO^- = HBrO \tag{4}$$

$$HBrO + \text{organic material} = CHBr_3 \tag{5}$$

Nitrates and nitrites:

Nitrogen from the atmosphere is mineralized by soil bacteria into ammonium. Under aerobic conditions, nitrogen is converted to nitrate by nitrifying bacteria. At excessive concentrations, nitrogen disrupts the production or delays crop maturation, and excessive amounts of nitrogen in irrigation water can cause serious problems. The production of nitrogen-sensitive crops can be influenced by nitrogen concentrations > 5 mg L^{-1}. Nitrates occur in ozonated water in small quantities. The limit values for irrigation are listed in Table 1. The value of nitrites recorded at the outlet of the WWTP was 0.557 mg L^{-1} that increased to 0.71 mg L^{-1} after treatment with ozone, whereas the nitrate values decreased from 1.12 to 0.22 mg L^{-1} after ozonation. Thus, the nitrite–nitrate contents of purified water treated with ozone complied with the standards for irrigation water (0–10 mg L^{-1}).

4. Microbiological quality

Table 2 summarises the bacteriological characteristics of the water leaving the WWTP and treated with ozone. Analysis of the results obtained revealed the elimination of E. coli indicators and considerable abatement of total coliforms (CT) and chlostridium by 94% and 64.72%, respectively. Furthermore, more than 98% of the faecal contamination was removed when Salmonellae and Vibrio cholerae were completely eliminated. Appreciable reductions in total streptococcal (T, St) (> 99%) and faecal streptococci (> 98%) were observed in purified water treated with ozone.

Note that the ozone water treatment device is an experimental setup for treating wastewater with a flowrate of 80 L min^{-1}. For higher values of flowrate, the number of ozone generators should be multiplied according to the existing flowrate of the wastewater treatment station.

5. Conclusion

The feasibility of an autonomous system of ozone water treatment at the Sidi-Bel-Abbes WWTP was investigated for recovery and reuse for irrigation of plants. Ozone treatment from an isolated site supplied by a photovoltaic system improved the physicochemical and bacterial qualities of the purified water intended for irrigation and were within the irrigation standards recommended by the WHO. The quality of the ozone-treated water was verified by other indicators, such as moderate electrical conductivity (1900 µS m^{-1}) and a pH less than 8.5. The iron and copper concentrations (0.0 mg L^{-1} and 0.05 mg L^{-1}) were below the maximum allowable limit (for ion 20 mg L^{-1}, for copper 3 mg L^{-1}). The low risk of sodium SAR (3.13) coupled with electrical conductivity results in water with medium salinity. Thus, the chemical quality of ozone-treated water is generally appropriate for agricultural use. The study also revealed the efficiency of the ozone treatment process, which can complement wastewater treatment plants.

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