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Efficiencies of solar light, solar/H_2O_2 and solar photo-Fenton processes for disinfection of turbid wastewaters

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ABSTRACT

The effect of turbidity on wastewater disinfection by solar light, solar/H_2O_2 and solar photo-Fenton processes was investigated. The current work focused mainly on the enhancement of disinfection efficiency of turbid wastewaters by the application of solar-based advanced oxidation processes. Inactivation of *Escherichia coli* and *Bacillus subtilis* spores were evaluated in domestic wastewater at different turbidity levels. In total, 50 and 30 mg/L of hydrogen peroxide concentrations were used for solar/H_2O_2 and solar photo-Fenton processes, respectively. Results showed that *E. coli* removal by solar light process decreased significantly from a maximum of 4.24-log to a minimum of 1.38-log with increasing turbidity levels of 0.2, 30 and 150 nephelometric turbidity unit. However, with the application of solar/H_2O_2 and solar photo-Fenton processes, disinfection efficiencies increased and substantially higher *E. coli* removals were obtained. The synergistic effect of solar light and hydroxyl radicals overcame the adverse effect of turbidity. Inactivation levels of *B. subtilis* spores did not change significantly by the application of solar-based advanced oxidation processes. The best *E. coli* inactivation level in turbid wastewaters was achieved with solar photo-Fenton process.

Keywords: Turbidity; Domestic wastewater; Solar light; Solar/H_2O_2; Solar photo-Fenton; *E. coli*; *B. subtilis* spores

1. Introduction

Disinfection which is a main unit of wastewater treatment has a great importance on both water reuse and protection of public health. Classical disinfection methods such as chlorination, ozonation and UV disinfection are widely used for wastewater disinfection [1,2]. However, it is known that these methods have several disadvantages. Chlorine and ozone cause the formation of mutagenic and carcinogenic disinfection by-products [1,3–5]. UVC radiation does not have a residual effect [1]. UVC disinfection and ozonation require high capital, maintenance and operation costs [1,4]. Additionally, these methods can be insufficient for the inactivation of some waterborne pathogens like *Cryptosporidium* sp. and *Giardia* sp. [6]. Thus, practical, cost-effective and environmentally friendly methods are in search and solar-based advanced oxidation processes are becoming prominent, especially countries receiving high amounts of solar light [7,8]. In recent years, a serious increase has been observed in the number of studies concerning various microorganisms inactivation by solar-based processes such as solar disinfection (SODIS), TiO_2 photocatalysis, solar/H_2O_2 and solar photo-Fenton [3,6,9–12].

Solar-based processes are affected by different factors such as dissolved oxygen concentration, microorganism type, water temperature, water composition [9], turbidity [8,13], UV light intensity [14], pH, solar radiation intensity, exposure time, ionic strength, reactor type [13], absorbance, organic compounds and salinity [15].

Turbidity is one of the most important parameters for UV and solar-based processes. Turbidity is a measure of light scattering effect of water and arises from fine suspended

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materials like clay, silt, plankton and other microscopic organisms. Turbidity prevents light penetration [2,8,16]. Solar light penetration is reduced by the scattering effect of particles. Regrowth in turbid water increases or accelerates as attached microorganisms are protected from light by the particles. As turbidity increases, inactivation rate decreases [17].

Microorganism type is another important factor affecting UV and solar-based processes. Microorganisms exhibit different sensitivity to disinfection, even various strains of a microorganism type [5]. Every microorganism shows different resistance to solar disinfection [4]. Spore forming bacteria are known as more resistant to solar disinfection [3]. *Escherichia coli* is widely preferred in solar disinfection studies as it is an indicator of fecal contamination [18,19]. *Bacillus subtilis* endospores are also used as an indicator of solar disinfection as they give an indication of solar light inactivation for pathogenic protozoa [19].

pH is a critical factor that affects the advanced oxidation processes, especially photo-Fenton process. The optimum pH for photo-Fenton process is 2.8–3 [20]. Higher pH values result in precipitation of ferric iron as ferric hydroxides. As dissolved iron was removed by precipitation from the water, photo-Fenton reaction and the formation of hydroxyl radicals slow down [21]. However, it must be stated that photo-Fenton process at pH 3 also has some disadvantages. pH adjustment steps are required before and after the photo-Fenton process. Acidification and neutralization should be employed to pull down the pH of wastewater to 3 before the process and to raise the pH to 6–8 after the process. Acidification and neutralization, especially for large volumes of wastewaters, will increase number of treatment steps and operational and maintenance costs [1]. To avoid these disadvantages, there is a tendency to carry out the photo-Fenton process at neutral or near-neutral pH values in recent years. There are many studies that reported successful results at neutral pH. Rubio et al. [22] stated that photo-Fenton process (1 mg/L Fe^{2+}, 10 mg/L H_2O_2) led to fastest bacterial inactivation in comparison with solar/H_2O_2 and only solar light processes for Milli-Q water, artificial seawater and lake water at pH 7.5–8. Spuhler et al. [23] reported that photo-Fenton process (0.6 mg/L Fe^{2+}, 10 mg/L H_2O_2) at near-neutral pH was the most efficient system for bacterial inactivation in waters containing inorganic ions or model natural organic matter. Ortega-Gomez et al. [20] achieved 6-log inactivation for *Enterococcus faecalis* by solar photo-Fenton process at neutral pH in simulated wastewater.

The efficiencies of solar light, solar/H_2O_2 and solar photo-Fenton processes for the disinfection of domestic wastewater with turbidity were investigated. There are various studies that investigated the effect of turbidity on solar light disinfection of ground water, natural water and drinking water [24–28]. Turbidity effect has not been the objective of domestic wastewater disinfection by solar light and solar-based advanced oxidation processes. The present study focused mainly on how microorganism removal efficiencies changed by the use of solar-based advanced oxidation processes in comparison with SODIS process for turbid wastewater disinfection at neutral pH. *E. coli* and *B. subtilis* spores were used in the experiments with the thought that behavior (resistance) of vegetative cells (*E. coli*) and spores (*B. subtilis*) will be different during the solar light process and the solar advanced oxidation processes.

2. Materials and methods

2.1. Preparation of microorganism cultures

E. coli (ATCC 25922) and *B. subtilis* (ATCC 6633) were used as model bacteria and purchased from American Type Culture Collection (ATCC). According to ATCC recommendations, *E. coli* was inoculated in Tryptic Soy Broth (TSB; Merck, Germany) and grown overnight to activate at 37°C with constant shaking in an orbital incubator. A loopful of bacteria was transferred on Tryptic Soy Agar (TSA) slants and after incubation, slants were stored at 4°C as stock culture. *E. coli* was subcultured on fresh TSA slants monthly.

Colonies on TSA slants were inoculated in 100 mL TSB and cultured at 37°C for 20 h in an orbital incubator. It was determined whether *E. coli* had reached to the stationary phase by measuring optical density at 595 nm (OD_{595}). Bacteria at the stationary phase were harvested by centrifugation at 5,000 rpm for 10 min and washed twice with ringer solution (Merck). Bacteria were resuspended in ringer solution and stored at 4°C. Bacterial concentration of this stock solution was approximately 10^8 CFU/mL.

Culture of *B. subtilis* was inoculated to TSB (Merck) and incubated at 35°C for 24 h in order to prepare a late log phase suspension of vegetative cells of *B. subtilis*. A 10^{-2} dilution of the suspension was prepared in a standard phosphate buffer containing $MnCl_2$. A 3-mL aliquot of the diluted suspension was poured on R2A Agar (BD, USA) to form a thin layer. The vegetative bacteria were allowed to incubate at 35°C for 7 d until 95% of the microorganisms had sporulated. The spore layer was scrapped with phosphate buffer and centrifugated at 5,300 rpm for 5 min. The spores were washed four times with a mixture of phosphate buffer-0.1% Tween-80. The spore stock was stored at 4°C [29]. Spore concentration of this stock solution was approximately 10^8–10^9 CFU/mL.

2.2. Enumeration of microorganisms

Bacterial colonies were enumerated by pour plate method on plate count agar (PCA) [30]. At each sampling time, 10 mL of sample was withdrawn and diluted serially by adding into 90 mL of ringer solution to obtain countable colony numbers in petri dishes (between 30 and 300 colonies per plate). Diluted samples (1 mL) were mixed with PCA in petri dishes and cream-colored colonies were counted after incubation at 37°C for 20 h. Bacterial numbers were estimated manually as CFU/mL. Plating was done in duplicates for each sample.

Detection and enumeration of viable spores of *B. subtilis* were performed using TSB containing 1% tetrazolium trichloride. The tetrazolium trichloride dye turned the spores red as they germinated, and ultimately formed red pin-head (slightly larger) colonies, aiding in the counting of microorganisms. Samples were pasteurized in a water bath at 75°C for 15 min. Plates were incubated at 35°C for 24 h and then counted [29,31].

2.3. Solar simulator

Sunlight was simulated by an SOL 2000 unit (Honle UV Technology). This unit is equipped with H2 filter to eliminate wavelengths below 295 nm. Spectral distribution of this lamp is between 295 and 3,000 nm (UVB + UVA + visible +

infrared). UVB, UVA and global solar irradiances reaching the water samples were 1.83, 30.5 and 400 W/m^2, respectively.

2.4. Reagents and analysis

Hydrogen peroxide (30%) was obtained from Merck and 1% solution was used to ensure different concentrations of H_2O_2 in experiments. Ferrous sulfate heptahydrate ($FeSO_4.7H_2O$, Merck) was used as an iron source. pH adjustment was made with 0.1 N NaOH (Riedel-de Haën, Germany) and 0.1 N HCl solutions (Merck). Residual hydrogen peroxide was removed with sodium sulfite (1 M; Merck). All solutions were prepared with distilled water.

OD_{595} was measured by a Hach Lange DR5000 spectrophotometer. pH was measured by a Hach Lange HQ40d portable multiparameter water analyzer (PHC10101). Turbidity was measured by a Hach Lange 2100Q Turbidimeter. The solar UVB (280–315 nm) and UVA (315–400 nm) irradiances were measured using Delta Ohm Multifunction Datalogger (DO9847) equipped with appropriate probes. The global radiation measurement (295–3000 nm) was performed with a pyranometer (Delta Ohm LPPYRA02).

2.5. Preparation of synthetic wastewater

Synthetic wastewater was prepared according to Organization for Economic Co-operation and Development (OECD) [32]. Chemical oxygen demand (COD) and dissolved organic carbon values of the synthetic wastewater were approximately 125 and 50 mg/L, respectively. Purified water was used for the preparation of synthetic wastewater.

2.6. Preparation of turbid water samples

Turbid water samples were prepared by addition of stock bentonite solution to synthetic wastewater to the required turbidity levels. After adding the bentonite powder (Riedel-de Haën) into purified water, it was shaken well and kept without mixing for 3 h to remove settleable solids and to confirm the presence of suspended solids during experiments. The supernatant was taken and autoclaved at 121°C for 15 min. Determination of the total suspended solids concentration of the stock bentonite solution was made according to Standard Methods 2540D [16].

2.7. Experimental procedure

Experiments were done as a batch system under solar simulator. Batch experiments were carried out in cylindrical glass beakers (diameter 8 cm, height 9.5 cm) filled with 200 mL of wastewater. The liquid depth in the beakers was 6.5 cm. The COD value of the wastewater was adjusted to 125 mg/L according to European Community for the simulation of urban wastewater treatment plant discharges [33]. Hydrogen peroxide was used at the concentration of 50 mg/L for solar/H_2O_2 process and 30 mg/L for solar photo-Fenton process. Fe^{2+} concentration was selected as 5.6 mg/L.

Before each test, Honle SOL 2000 unit was turned on for at least 10 min to ensure a uniform lamp output. pH of wastewater was adjusted to 7 by using NaOH or HCl. For solar photo-Fenton experiments, iron addition was made before pH adjustment. Microorganisms were inoculated in required numbers (i.e., 10^5–10^6 CFU/mL for *E. coli*, 10^4 CFU/mL for *B. subtilis* spores), and water samples were mixed thoroughly with a magnetic bar, and finally, H_2O_2 was added in required concentrations. Water samples were placed under the solar simulator and exposed to the light for a duration of 120 min. Samples were taken from the glass beakers at 0, 15, 30, 45, 60, 75, 90, 100, 110 and 120 min and mixed with appropriate amounts of sodium sulfite to remove residual H_2O_2. Then, the analyses of *E. coli* and *B. subtilis* spores were performed. All experiments were repeated twice.

3. Results and discussion

Disinfection of domestic wastewaters by solar light, solar/H_2O_2 and solar photo-Fenton processes and the effect of turbidity on these processes at neutral pH were investigated. Experiments were performed with particle-free, low-turbidity and high-turbidity wastewaters. The turbidity values were chosen according to European Community total suspended solid requirements for discharges from urban wastewater treatment plants [33]. The turbidity values for wastewaters containing 0, 35 and 150 mg/L total suspended solids were 0.2, 30 and 150 nephelometric turbidity unit (NTU) for solar light and solar/H_2O_2 processes and 3, 37 and 158 NTU for solar photo-Fenton process, respectively. The increase in turbidity for solar photo-Fenton process was due to the yellowish color generated by Fe^{2+}.

Figs. 1(a)–(c) show the effect of turbidity on the removal of *E. coli* by solar light, solar/H_2O_2 and solar photo-Fenton processes. *E. coli* removal efficiency gradually decreased with the increase in turbidity levels from 0.2 to 30 NTU and 150 NTU for solar light process (Fig. 1(a)). With the application of solar light for 120 min, 4.24-log removal was obtained in water with a turbidity of 0.2 NTU. Removal values decreased to 2.91-log and 1.38-log for waters with the turbidity of 30 and 150 NTU, respectively, as the increased solid particle concentration prevented the light transmission into the wastewater. *E. coli* in wastewater was not removed completely with solar light process and maximum log removal that was reached with 120 min of light exposure was 4.24-log in particle-free water.

According to Fig. 1(b), the log reductions of *E. coli* by solar/H_2O_2 process at 45th min were 5.64-log, 3.86-log and 3.34-log for turbidities of 0.2, 30 and 150 NTU, respectively. For the 60th min, 5.65-log reduction was achieved for all turbidity levels and *E. coli* in wastewater was removed completely.

Examination of Fig. 1(c) indicated that higher than 5-log *E. coli* removal was achieved in a shorter time (i.e., 30 min) by solar photo-Fenton process. There was no difference between the results of turbidity levels of 3 and 37 NTU for solar photo-Fenton process. At the 30th min of the process, 5.87-log *E. coli* removal was achieved in waters with turbidities of 3 and 37 NTU, whereas 3.92-log removal was obtained in water with the turbidity of 158 NTU. Reduction of *E. coli* was approximately 6.03-log after 45 min of solar photo-Fenton process for all turbidity levels and complete *E. coli* inactivation was achieved.

Gomez-Couso et al. [26] investigated the efficiency of SODIS process in turbid waters containing *Cryptosporidium* *parvum* oocysts and reported that the efficiency of SODIS process decreased with increasing turbidity (0, 5, 100, 300 NTU). Kehoe et al. [27] stated that *E. coli* inactivation rates decrease and longer inactivation times are required with increased turbidity by SODIS process for disinfection of drinking waters. Less *E. coli* removal was obtained by solar light process and long period of exposure times were required to reach higher removal levels. However, solar/H_2O_2 and solar photo-Fenton processes reduced the counteracting effect of turbidity substantially and appeared to reach higher removals in shorter times as compared with solar light process. Microorganism inactivation by solar/H_2O_2 process and solar photo-Fenton process occurs as a result of multiple inactivation mechanism by solar radiation and hydroxyl radicals produced by solar radiation–H_2O_2–Fe^{2+} reactions. Therefore, suppressed inactivation effect of turbidity on solar radiation is compensated with hydroxyl radicals produced in solar/H_2O_2 and solar photo-Fenton processes.

When compared to solar/H_2O_2 process, the addition of iron to wastewater caused a significant reduction in inactivation times at neutral pH for simulated wastewater used. Ortega-Gomez et al. [11] reported that solar/H_2O_2 led to complete *E. coli* and total coliform inactivation within 60 and 120 min while solar photo-Fenton achieved total inactivation of *E. coli* and total coliform within 45 and 60 min in real municipal wastewater at neutral pH. Ortega-Gomez et al. [20] stated that solar/H_2O_2 led to a 4-log bacterial decrease after 100 min while solar photo-Fenton led to a 6-log bacterial decrease after 40 min in simulated wastewater at neutral pH. For solar/H_2O_2 process, damaged cells by the exposure to solar light become weaker to H_2O_2 and cell death occurs by hydroxyl radicals which result from reactions of intracellular iron structures and H_2O_2 entering into the cell [34]. For solar photo-Fenton process, microorganism inactivation takes place with the formation of hydroxyl radicals within and outside of the cell. Hydroxyl radicals are formed with chain reactions of solar light/Fe^{2+}/H_2O_2 outside the cell. Fe^{2+} and H_2O_2 entering into the cell increase intracellular concentrations of these agents and Fenton reactions inside the cell cause the formation of hydroxyl radicals and cell death occurs [1,34]. Thus, more hydroxyl radicals were produced by solar photo-Fenton process resulting in higher disinfection efficiencies in shorter times.

Figs. 2(a)–(c) show the effect of turbidity on the removal of *B. subtilis* spores by solar light, solar/H_2O_2 and solar photo-Fenton processes. Experiments were performed at neutral pH and with low-turbidity and particle-free wastewaters.

Fig. 2(a) illustrates the effect of solar light process on *B. subtilis* spores inactivation and it is shown that the inactivation rate was not influenced by the turbidity of wastewater. Only 0.57-log reduction was achieved after exposure time of 120 min in turbid (30 NTU) water compared with 0.67-log reduction in particle-free water. Performance of the solar light process appeared to be very poor for the removal of *B. subtilis*

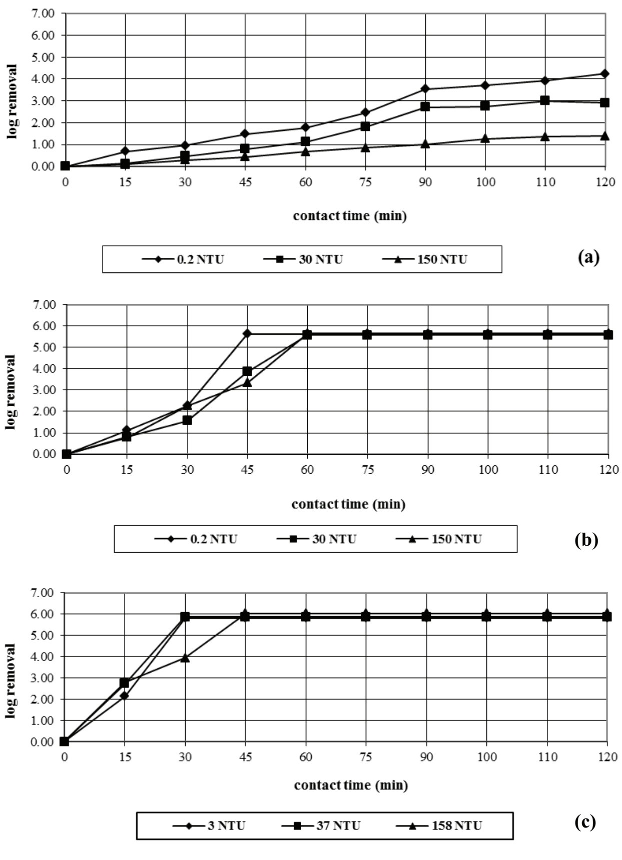

Fig. 1. The effect of turbidity on solar processes for *E. coli*; (a) solar light, (b) solar/H_2O_2 and (c) solar photo-Fenton.

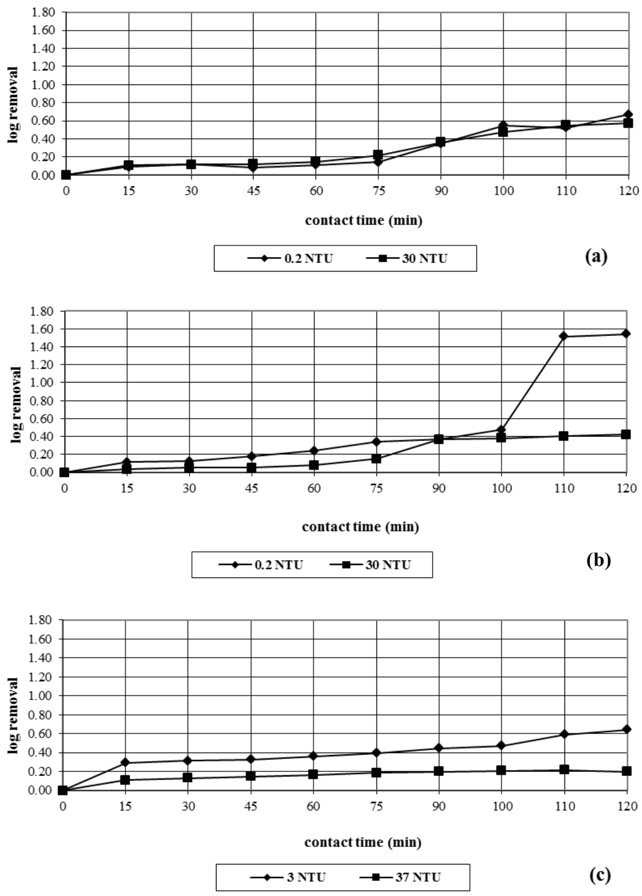

Fig. 2. The effect of turbidity on solar processes for *B. subtilis* spores; (a) solar light, (b) solar/H_2O_2 and (c) solar photo-Fenton.

spores. Boyle et al. [35] reported that maximum removal of *B. subtilis* spores that attained after cumulative 16 h of strong solar light exposure was only 1.3-log.

It was thought that spore coat layers contribute to the resistance of spores to UVA and UVB light [36]. Besides, spores have a different DNA photochemistry when they are exposed to long-wavelength UV radiation and various photo-products are produced [37,38]. However, spore coat layers do not have a function in the resistance against UVC radiation [36]. Thus, spores that are exposed to UV radiation above 295 nm are expected to have higher resistance [38].

Fig. 2(b) illustrates that 1.54-log reduction was achieved and the initial spore concentration was reduced from 10^4 to 10^3 CFU/mL by solar/H_2O_2 process for particle-free water. Spore inactivation decreased to 0.42-log reduction when turbidity was increased to 30 NTU. The negative effect of turbidity on disinfection efficiency was more apparent for solar/H_2O_2 process in comparison with solar light process. It was assumed that the inactivation of *B. subtilis* spores was not affected by H_2O_2 or hydroxyl radicals. Eleren et al. [15] investigated the inactivation efficiency of *B. subtilis* spores by solar light and solar/H_2O_2 processes in surface waters containing fulvic acid and reported that the addition of H_2O_2 to the environment did not provide a contribution to the removal of *B. subtilis* spores. Mamane et al. [38] stated that H_2O_2, UV > 295 nm, UV/H_2O_2 processes and also formed hydroxyl radicals have no effect on *B. subtilis* spores inactivation.

Spore coat is known to act as a diffusion barrier against hydrogen peroxide preventing to reach target sites or spore coat proteins react with hydrogen peroxide and effective H_2O_2 concentration is reduced before reaching target sites [36,38]. Besides, the protection of spore DNA from free radical damage is associated with binding of small, acid-soluble proteins in the core to the spore DNA. Additionally, spores show resistance to oxidizing agents such as hydroxyl radicals due to the low permeability of inner membrane against hydrophobic and hydrophilic molecules [5,39]. Teksoy et al. [5] reported that increasing H_2O_2 concentrations were less effective in *B. subtilis* spores inactivation in comparison with *E. coli* and *Pseudomonas aeruginosa*. The presence of H_2O_2 and hydroxyl radicals appear unlikely to contribute significantly to the inactivation of *B. subtilis* spores.

Examination of Fig. 2(c) indicated that the solar photo-Fenton process was not efficient for the inactivation of *B. subtilis* spores. 0.64-log and 0.2-log removals were obtained after the exposure time of 120 min with the turbidity levels of 3 and 37 NTU, respectively. As explained earlier, H_2O_2 and hydroxyl radicals were expected not to contribute significantly to the inactivation. In addition, iron might have a negative effect on the process. The nature of iron species in water is pH dependent. At acidic pH, iron is in the form of hexaaquo ion ($Fe(H_2O)_6^{3+}$) while at higher pH values, this ion precipitates as amorphous ferric oxyhydroxides [3]. Therefore, the potential of hydroxyl radical formation reduces and the turbidity and yellow-orange color of the water increases. In this study, while hydroxyl radicals were not significant in the inactivation of *B. subtilis* spores, prevention of solar light penetration might reduce inactivation.

Comparison of the three processes for *E. coli* inactivation was demonstrated in Fig. 3. The efficiency order of the processes was as follows: solar photo-Fenton > solar/H_2O_2 > solar light. *E. coli* was completely removed by solar photo-Fenton process while 3.34-log removal was achieved by solar/H_2O_2 process at 45th min. However, the removal by solar light process did not reach even 1-log. *E. coli* was inactivated completely by solar/H_2O_2 process at 60th min, whereas complete removal of *E. coli* never occurred for the solar light process. Microorganism inactivation took place by the effect of both solar light and hydroxyl radicals for solar photo-Fenton and solar/H_2O_2 processes. However, as explained previously, formation of hydroxyl radicals by solar photo-Fenton process occurs inside and outside of the cell, resulting in an increase in disinfection efficiency. The formation of hydroxyl radicals is only limited to intracellular free iron pool for solar/H_2O_2 process. In the case of solar photo-Fenton process, even though intracellular iron was ended by Fenton and Haber–Weiss reactions, the catalytic cycle between the Fe^{2+}, Fe^{3+}, H_2O_2 and UV–Vis light photons proceeded outside the cell continue to generate hydroxyl radicals.

Experimental results indicated that *B. subtilis* spores were more resistant than *E. coli* to all processes under all experimental conditions. The maximum *B. subtilis* spores removal values were 0.57-log and 1.54-log, whereas the minimum *E. coli* removal values were 4.24-log and 2.91-log for particle-free and low-turbidity wastewaters, respectively. Agullo-Barcelo et al. [6] investigated the removal of bacteria, spores and viruses from real secondary effluent from a municipal treatment plant by solar-based advanced oxidation processes and stated that sulfite-reducing clostridia spores were the most resistant indicator in all processes. It was concluded that the reason for *B. subtilis* spores removal was less than *E. coli* removal and this may be attributed to both lack of contribution of H_2O_2 and hydroxyl radicals to the inactivation process and also to the structure of spores.

Some researchers have evaluated solar advanced oxidation processes in real and synthetic wastewaters for the inactivation of different microorganisms such as *E. coli*, *E. faecalis*, total coliforms, *Fusarium solani*, antibiotic resistant *E. coli* at various pH, turbidity levels and catalyst concentrations [1,6,11,20,40,41].

Ferro et al. [41] compared the performance of solar light and solar-based advanced oxidation processes on the inactivation of antibiotic resistant *E. coli* in real biologically treated

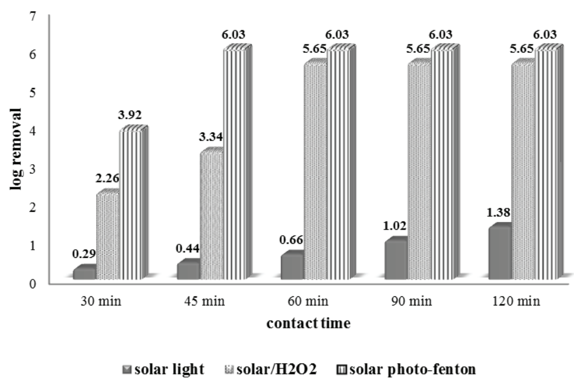

Fig. 3. Comparison of *E. coli* inactivation by solar light, solar/H_2O_2 and solar photo-Fenton processes at different contact times at high turbidity level (150 and 158 NTU).

wastewater with the turbidity of 50 ± 16 NTU and they stated that total inactivation (about 5-log) was obtained at the end of 4 h by solar light process. The exposure time needed to reach the detection limit decreased to 120 and 20 min with the application of 50 mg/L H_2O_2 under solar light and solar photo-Fenton at pH 4. For photo-Fenton experiments, with the ratio of Fe^{2+}/H_2O_2:5/10 mg/L, the exposure times needed to reach detection limit were 4 h and 20 min at pH 8.9 and pH 4, respectively. They stated that the dissolved iron concentration at pH 8.9 was zero or below the detection limit. Agullo-Barcelo et al. [6] obtained 4-log *E. coli* reduction in 5 h by solar light disinfection of municipal wastewaters with the turbidity of 8 ± 4 NTU. For solar/20 mg/L H_2O_2 and solar photo-Fenton (pH 3) processes, time required to obtain 4-log removal decreased to 1.95 and 0.12 h, respectively. They stated that at pH 7, detection limit was reached in about 2.5 h because of the iron precipitation. For the present study, photo-Fenton experiments with *E. coli* the times needed to reach detection limit were 30 min for 3 and 37 NTU and 45 min for 158 NTU at neutral pH (pH 7) (Fig. 1(c)). The reason for the reduced times in our study may be attributed to the presence of dissolved iron (data not shown) in wastewater.

Ortega-Gomez et al. [11] stated that solar light disinfection led to 1-log decrease of total coliforms after 3 h in real secondary effluents containing turbidity of 8.98 ± 4.2 NTU and they stated that the photo-Fenton process reduced exposure time to 60 min. All these researchers [6,11,41] stated that solar advanced oxidation processes ensure higher disinfection efficiencies and shorter inactivation times in comparison with solar light process that are consistent with our results. However, the aim of these studies was to evaluate disinfection efficiencies by solar advanced oxidation processes, not to evaluate the turbidity effect. The present study evaluated the disinfection of *E. coli* and *B. subtilis* spores by the solar light and the solar-based advanced oxidation processes for domestic wastewater with varying turbidities at neutral pH.

Results indicated that complete inactivation of *E. coli* was possible within 45 min with the solar photo-Fenton process and within 60 min with the solar/H_2O_2 process for wastewaters containing 150 NTU turbidity (i.e., highly turbid water). Only 0.66-log removal efficiency within 60 min with the solar light process for the same condition demonstrated the superior efficiencies of the solar-based advanced oxidation processes.

4. Conclusions

The effect of turbidity on disinfection of wastewater by solar light process and solar-based advanced oxidation processes was evaluated. Efficiency of solar light process may be reduced in turbid waters to a significant level.

Complete inactivation of *E. coli* was not achieved with the solar light process. Higher inactivation levels were obtained in shorter exposure times by solar/H_2O_2 and solar photo-Fenton processes for *E. coli* in comparison with solar light process. For high-turbidity wastewaters, only 1.38-log reduction was obtained at the end of the solar light process (i.e., 120th min), whereas 5.65-log and 6.03-log removals were reached at 60th min and 45th min by solar/H_2O_2 and solar photo-Fenton processes, respectively. However, for *B. subtilis* spores, inactivation was limited and solar/H_2O_2 and solar photo-Fenton processes did not enhance the disinfection efficiency significantly. Log reduction values (at 120th min) for *B. subtilis* spores varied between 0.20-log and log/0.67-log in general except for the solar/H_2O_2 process where 1.54-log removal was obtained.

Particle removal processes must be employed before the application of solar light process for an efficient disinfection. However, it is worth noting that with the application of solar-based advanced oxidation processes, requirement for the preliminary treatment processes such as filtration, sedimentation may be eliminated in order to reduce costs.

Results of the present study clearly demonstrated that efficiency of the solar light process in turbid waters can be enhanced to a significant level by the application of solar-based advanced oxidation processes. The use of solar photo-Fenton and solar/H_2O_2 processes enhanced disinfection efficiency of turbid wastewaters, even for high-turbidity levels, in comparison with SODIS process. Main reason for the increase in disinfection efficiency appear to be the generation of oxidative agents such as H_2O_2, OH•, HO_2• that inactivate bacterial cells that are protected from the solar light due to adsorption to particles, rich nutrient environment provided by particles and shielding effect of particles.

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