Effects of Sodium Sulfate and Sodium Chloride for Sonochemical Degradation on 1,4-benzoquinone and Hydroquinone in Aqueous Solution

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ABSTRACT

1,4-benzoquinone, with the molecular formula $C_6H_4O_2$, is generally known as a para-quinone. It is a six-member ring compound with an oxidized derivative known as 1,4-hydroquinone, which is a bright yellow crystal that has an irritating odour. On the other hand, hydroquinone, also known as benzene-1,4-diol, has the chemical formula $C_6H_4(OH)_2$. It looks like a white granular solid. Quinone is generally used as a precursor to hydroquinone. The skeletal muscle relaxant, ganglion blocking agent, benzoquinonium, is made from benzoquinone. It is utilized to suppress double-bond migrations during olefin metathesis reactions. 1,4-benzoquinone is also used in the synthesis of Bromodol, while hydroquinone is the main ingredient in black-and-white photographic developers such as film and paper developers, where it diminishes the silver halide to elemental silver. There are various other uses related to this diminishing power. As a polymerization inhibitor, hydroquinone prevents the polymerization of methyl methacrylate, acrylic acid, etc. Studies have demonstrated the various effects of Na_2SO_4 and NaCl on the sonochemical degradation of 1,4-benzoquinone and hydroquinone using a 200-kHz sonicator. The highest degradation rate was obtained in the presence of 0.433 M Na_2SO_4 for 1,4-benzoquinone. After 30 minutes of ultrasonic irradiation, the total concentration of 1,4-benzoquinone decreased to 99% in the presence 0.433 M Na_2SO_4. Without Na_2SO_4, the sonochemical degradation rate of 1,4-benzoquinone was 4.5 times higher than that of hydroquinone, whereas in the presence of 0.433 M Na_2SO_4 under the same conditions the initial reaction rate of 1,4-benzoquinone was increased to become 10.6 times higher than that of hydroquinone. On the other hand, in the presence of NaCl, no effects were observed for the decomposition of hydroquinone but negative effects were clearly observed for the decomposition of 1,4-benzoquinone.

Keywords: 1,4-benzoquinone; Hydroquinone; Na_2SO_4; NaCl; Sonication

INTRODUCTION

For the last few decades, Advanced Oxidation Processes (AOPs) such as O_3, UV with H_2O_2, UV with O_3, Fe^{2+} with H_2O_2 and UV with O_3 and H_2O_2 have become visible as undertaking technologies for the degradation of uncooperative organic hazardous wastes (Rosenfeldt et al. 2004; Spanggord et al. 2000 & Anotai et al. 2006). AOPs produce ·OH radicals which has redox potential 2.8 V vs. Normal Hydrogen Electrode (NHE) are strongly reactive for organic pollutants. At present, applications of new AOPs with SO_4^{2-} radicals which are formed via reaction of OH radicals with sulfate ions has been investigated because SO_4^{2-} radical anion (E^0 = 2.5-3.1 V vs. NHE) also possess high oxidation potential. There are various researches have been brought out by the use of SO_4^{2-} radicals for the decomposition of a variety of organic pollutants (Waldemer et al. 2007; Fernandez et al. 2004; Bandala et al. 2007 & Hori et al. 2005).

Sonochemical degradation method is a promising one because maximum reaction conditions including pyrolysis and radical reactions are generated via the formation of cavitation bubbles with high temperatures and pressures.

As for sonolysis in aqueous solutions, hydroxyl radicals are produced through the expeditious collapse of cavitation bubbles (Makino et al. 1983 & Riesz et al. 1985). So that, the sonochemical degradation method has raised a wide attention in environmental applications such as organic pollutants control (Mallakpour et al. 2014 & Saccani et al. 2014), biological hydrogen production (Guo et al. 2011 & Yang et al. 2012), and excess sludge reduction (He et al. 2011; Yang et al. 2013 & Guo et al. 2013). Sonochemical degradation of phenol and phenolic compounds has been investigated by several researchers and investigated some intermediates such as hydroquinone, benzoquinone, catechol (Lim et al. 2014; Jyothi et al. 2014; Rokhina et al. 2013; Wang et al. 2013; Verma et al. 2013; Sakakura & Mitsuo 2012; Joseph et al. 2011; Zhang et al. 2011; Torres-Palma et al. 2010; Berlan et al. 1994; Entezari et al. 2003; Petrier et al. 1994; Dükkancı et al. 2006 & Serpone et al. 1993). These compounds further decomposed into more hydrophilic compounds that is formic and oxalic acid (Dukkanc et al. 2006 & Yim et al. 2003).

Although there are many reports for sonochemical degradation of phenol and phenolic compounds (Lim et al. 2014; Jyothi et al. 2014; Rokhina et al. 2013; Wang et al.

2013; Verma et al. 2013; Sakakura & Mitsuo 2012; Joseph et al. 2011; Zhang et al. 2011, and Torres-Palma et al. 2010), to the best of our knowledge, sonochemical decomposition of 1,4-benzoquinone and hydroquinone under argon gas pressure is not reported.

In this study, we performed the sonchemical degradation of 1,4-benzoquinone and hydroquinone in an aqueous solution at a frequency of 200 kHz. The lack of the research is we have performed 30 minutes of experiment and used only two inorganic salts. 1,4-benzoquinone provide an influence to both powerful mineral acids and alkali, which phenomenon condensation and decomposition of the composite. Its acute toxicity (oral LD50: 130 mg/kg body weight for rats) (Patnaik 2007). On the other hand acute toxicity of hydroquinone (oral LD50 value for both sexes combined was >375 mg/kg) (Topping et al. 2007). As electron acceptor benzoquinones perform a vital role in the breathing organisms (Okamura et al. 2000 & Kawamukai 2002). Consequent to UV irradiation of benzoquinone by-products in aqueous media, hydroxyquinone and oxygen are produced (Leighton et al. 1929; Lente et al. 2004 & Joschek et al. 1966). The oxidation of diverse quinones to hydroxyquinones was expressed in the research (Spyroudis 2000).

On the other hand, hydroquinone is considered the main potential molecular messengers for semiquinone-type natives in the ignition of complicated polymeric and oligomeric arrangements accommodated in biomass components. Hydroquinone and its outgrowths are strong registered products of the ignition and pyrolysis of frequent types of biomass, as well as tobacco (Visser et al. 1985 and Lee et al. 1999). Consumption of hydroquinone has been displayed to induce choking, oxidizing impression, affected breathing in humans over and above reduced bone marrow and corneal damage in mice (Bilimoria et al. 1975 and Leanderson & Christer 1992). For all that, the discarding interest with hydroquinone in ignition and pyrolysis is its deterioration to produce persistent, semiquinone-type free radicals and other toxic outgrowths. It is acknowledged that pyrolysis of hydroquinone edges to the construction of p-benzoquinone and phenol (Sakai & Masayuki 1976 and Khachatryan et al. 2006) over and above a number of other aromatic and polycyclic aromatic hydrocarbon products (Ledesma et al. 2002 and Marsh et al. 2004). In this paper, we analyzed the effects of Na_2SO_4 and NaCl on the sonochemical decomposition of 1,4-benzoquinone and hydroquinone to enhance the rate of degradation. In addition, we also suggested that the degradation mechanism of 1,4-benzoquinone and hydroquinone was different from that of other phenolic compounds. Na_2SO_4 and NaCl also known as degrading agent in AOPs. Uddin et al. (2016) published on sonochemical decomposition in presence of inorganic salts corresponded of no effect or slight negative or positive effects.

EXPERIMENTAL SECTION

1,4-bezoquinone purity 98%, hydroquinone, sodium sulfate (anhydrous) both purity 99%, and sodium chloride purity 99.5% was purchased from Wako Pure Chemical Industries, Ltd. Japan. All the chemicals were reagent grade and used after received. Decontaminated water (18.2 MΩ cm resistivity) was prepared from a Millipore Milli-Q Gradient water purification system and was used to prepare all aqueous solutions. Argon (99.999% purity) was purchased from Osaka Sanso, Japan.

SONOLYSIS

Ultrasonic generator (Kaijo 4021, Lot no. 1033, MFG. no. 34C3) and a oscillator of 65 mm inner diameter were used for sonochemical degradation and were control at 200 kHz with an input power of 200 W. The glass vessel with a gross volume of 60 ml sample solution was used for ultrasonic irradiation under argon atmosphere. The vessel had a side arm with a silicon rubber septum for argon gas bubbling and sample extracting (every 0, 5, 10, 20 and 30 min) by the glass syringe (1 ml) without exposing the sample to air.
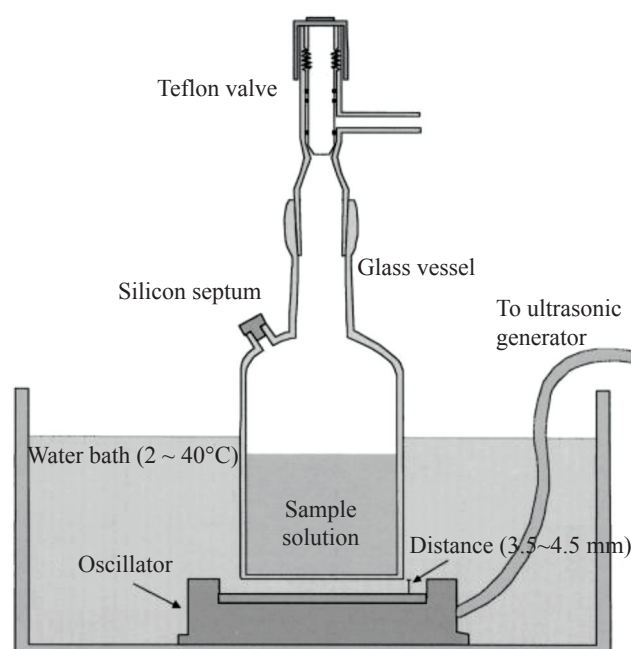

FIGURE 1. The schematic diagram of experimental setup for sonolysis (Okitsu et al. 2002).

The schematic diagram of the experimental setup as shown in Figure 1 was described in the literature (Okitsu et al. 2002). The glass vessel was flat bottomed and 1 mm thick. The vessel was climb up at a constant position (4 mm from the oscillator). The sonicated solution concentrations were determined with a HPLC.

When a wave experiences any inequality in the belongings of the channel in which it is propagating, its way of behaving is disturbed. Moderately changes in the way extending over many wavelengths conduct mostly to alter in wave speed and generate direction-the phenomenon of refraction. Sonochemical power usually indicated as the electrical input or output power to and from the generator. Several procedures are available to evaluate the amount of ultrasonic power entered into a sonochemical reaction (Mason 1991). Calorimetric method, that involves computation of the initial rate of a temperature increase produced when a system is illuminated by power ultrasound. This is established on the supposition that almost all the mechanical energy fabricates heat and thus the output power can be procured via calorimetry. In the present experiment, acoustic energy was measured by the calorimetric method.

For one and all system the temperature (T) in the reaction cell was recorded against time (t) at 10s, intervals, using a thermocouple placed in the reaction vessel. From the T versus t data, total acoustic power can be calculated using the Equation (1).

$$Pw = m \, Cp \, (\Delta T / \Delta t) \qquad (1)$$

Where,

Pw = power (Watt),
m = mass of water used (100 g),

Cp = heat capacity of water ($4.18 \, J.g^{-1}K^{-1}$),
ΔT = temperature rise [(28.2-27.1) = 1.1°C],
Δt = interval of time (30s).

Before and after ultrasonic irradiation, the inside reactor cell temperature of water was thermostated at room temperature. Calorimetric power quantifications were carried out three times under the same conditions, and the volume of solution in the reaction vessel was 60 g. The calorimetric power was input in the cell was around 15 W.

RESULTS AND DISCUSSION

Throughout the sonolysis of water, it is popular that acoustic cavitation originates highly reactive primary radicals such as OH and H due to the thermal decomposition of water as shown in Equation (2) (Ashokkumar et al. 2008 & 2004). A number of recombination and other reactions (Equations (3)-(4)) occur. The OH radical is a nonselective oxidant with a high redox potential (2.8 V), having the power to oxidize most organic pollutants.

$$H_2O \,))))))\rightarrow HO\cdot + H\cdot \qquad (2)$$
$$HO\cdot + H\cdot \rightarrow H_2O \qquad (3)$$
$$HO\cdot + HO\cdot \rightarrow H_2O_2 \qquad (4)$$

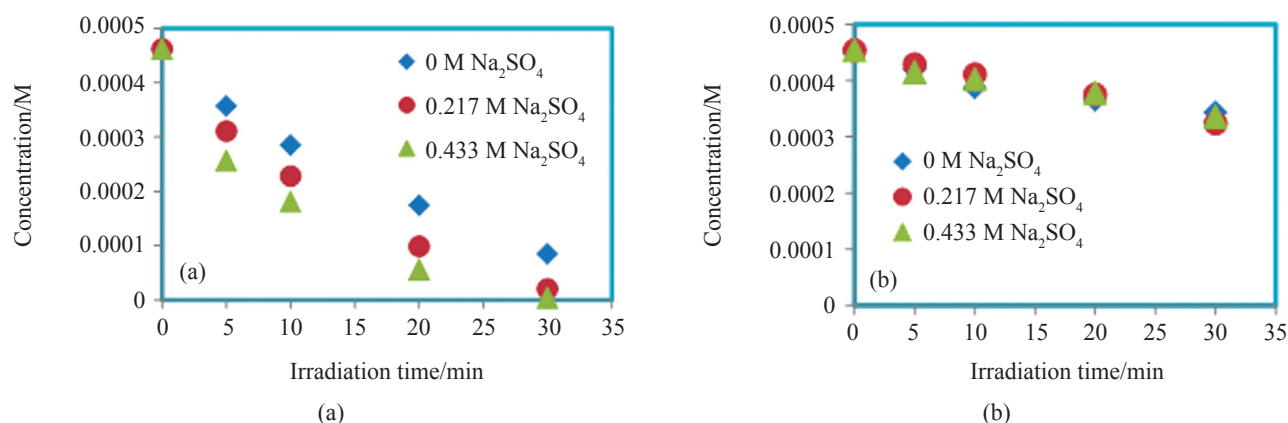where "))))))" refers to sonication.

FIGURE 2. Effects of sonochemical degradation of a) 1,4-benzoquinone and b) hydroquinone in absence and presence of Na_2SO_4.

Sonochemical degradation of 1,4-benzoquinone and hydroquinone was inquired into the absence and presence of Na_2SO_4 respectively using UV-vis spectrophotometer. Figure 2(a) and (b) show the effects of sonochemical degradation of 1,4-benzoquinone and hydroquinone in the absence and presence of various concentrations of Na_2SO_4. Figure 1(a) shows, the initial rate of sonochemical decomposition of 1,4-benzoquinone increased 2.8 times in presence of 0.433 M Na_2SO_4 than in absence of Na_2SO_4. In contrast, at same concentration of Na_2SO_4 the sonochemical degradation of hydroquinone was not increased conspicuously as shown in Figure 2(b).

Therefore, to understand the sonochemical degradation mechanism of 1,4-benzoquinone and hydroquinone research was performed in presence of different electrolytes such as Na_2SO_4 and NaCl using HPLC. Figure 2 also shows change in the concentration of phenolic compounds throughout sonication under Ar atmosphere. From Figure 2, it was observed that the degradation rates of 1,4-benzoquinone was strongly affected by the addition of Na_2SO_4, on the other hand hydroquinone was slightly affected by the addition of Na_2SO_4. After 30 min ultrasonic irradiation reaction, the total concentration of 1,4-benzozuinone was decreased 99% in the presence of 0.433 M Na_2SO_4. The initial rate of

1,4-benzoquinone (in presence of 0.433 M Na_2SO_4) was increased 2.6 times than in the absence of Na_2SO_4. On the other study, in the presence of same concentration of Na_2SO_4, during sonochemical degradation of hydroquinone the decomposition rate slightly increased. In the presence of 0.433 M Na_2SO_4, after 30 min sonication the total concentration of hydroquinone decreased only 26%, whereas in the absence of Na_2SO_4 it was 24%. From Figure 3 experimentally observed in absence and presence of Na_2SO_4 the rates of sonochemical decomposition of 1,4-benzoquinone and hydroquinone were different. Figure 2 shows the comparison on time dependence of sonochemical degradation of 1,4-benzoquinone and hydroquinone in absence and presence of Na_2SO_4.
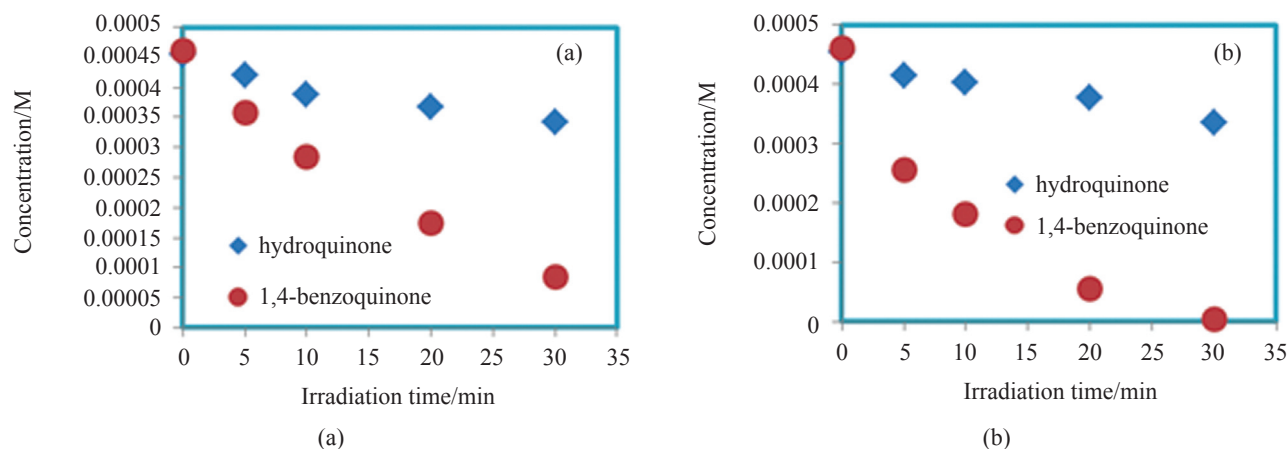

FIGURE 3. Comparison on time dependence of sonochemical decomposition of 1,4-benzoquinone and hydroquinone in the a) absence, b) presence of Na_2SO_4.

Figure 3 clearly shows that, the sonochemical degradation rate of 1,4-benzoquinone in the absence of Na_2SO_4 was 4.5 times higher than hydroquinone, whereas in presence of 0.433 M Na_2SO_4 at same condition the 1,4-benzoquinone reaction rate was increased 10.6 times higher than hydroquinone. The pKa values of 1,4-benzoquinone and hydroquinone were 4.2 and 4.0 respectively. In the particular case of 1,4-benzoquinone that reported in a cyclic voltammetric study of the aqueous electrochemistry system. The common shape of the potential-pH diagrams for the other quinones were similar to that of 1,4-benzoquinone, but not hydroxyquinone (Bailey et al. 1985).

We also explored the effects of NaCl on the rate of sonochemical decomposition 1,4-benzoquinone and hydroquinone. Even in the case of NaCl, no effect was observed for hydroquinone but clearly observed negative effect for 1,4-benzoquinone sonication as seen in Figure 4.

In the absence of salt, the initial rates of sonochemical degradation 1,4-benzoquinone were faster than those of hydroquinone. It is well known that the hydrophobicity of an organic solute is one of the most important parameters for sonochemical decomposition, because highly hydrophobic compounds tend to concentrate at the gas liquid interface where the concentration of OH radicals is very high (Henglein et al. 1985). To confirm hydrophobicity of solutes, we measured log P of these compounds and found that 1,4-benzoquinone (log P = 0.16*, 0.19 (Moret et al. 1996) and hydroquinone (log P = 0.58*, 0.59 (Veith et al. 1979), here, * symbol indicates experimental value.

Nanzai et al. mentioned that aromatic compounds decomposition rate increased with increasing value of log P (Nanzai et al. 2008) but present results were contradictory with Nanzai et al. The addition of Na_2SO_4 significantly affects the rates of decomposition for 1,4-benzoquinone, but addition of NaCl does not clearly affect the decomposition rates for 1,4-benzoquinone. Cheng et al. (2010) observed, $NaHCO_3$ and Na_2SO_4 are found to reduce the sonochemical rate constants for PFOX (X = S or A; perfluorooctane sulfonate or perfluorooctanoate respectively).

The results of present research were reverse with Hofmeister series. Paterova' et al. (2013) observed completely reversed Hofmeister series and correlative with present results. In presence of Na_2SO_4 sonolysis of 1,4-benzoquinone significantly enhanced the rate of decomposition, on the other hand, at same condition sonolysis of hydroquinone was slightly/not enhanced the rate of degradation as shown in Figure 2. In presence of NaCl, sonolysis of 1,4-benzoquinone reduced the rate of degradation reaction that is negative effect observed. On the other hand at the same condition, sonolysis of hydroquinone no effect was found (as shown in Figure 4).

Hydroquinone is a reducing agent that is reversibly oxidizable to quinone. The oxidation potential of hydroquinone at 20°C and pH 7.03 is 0.2982 volts. Quinones are suggested to be a dominant redox-active moiety within natural organic matter (Nurmi & Paul 2002) and humic substances (Scott et al. 1998). Electron transfer to quinones can be expected to lead to an increase in semiquinone radical intermediates as well as hydroquinone Figure 6. Figure 5 shows the time dependence of 1,4-benzoquinone sonication in the absence and presence of different concentration of Na_2SO_4. It was observed that 1,4-benzoquinone was degraded under argon
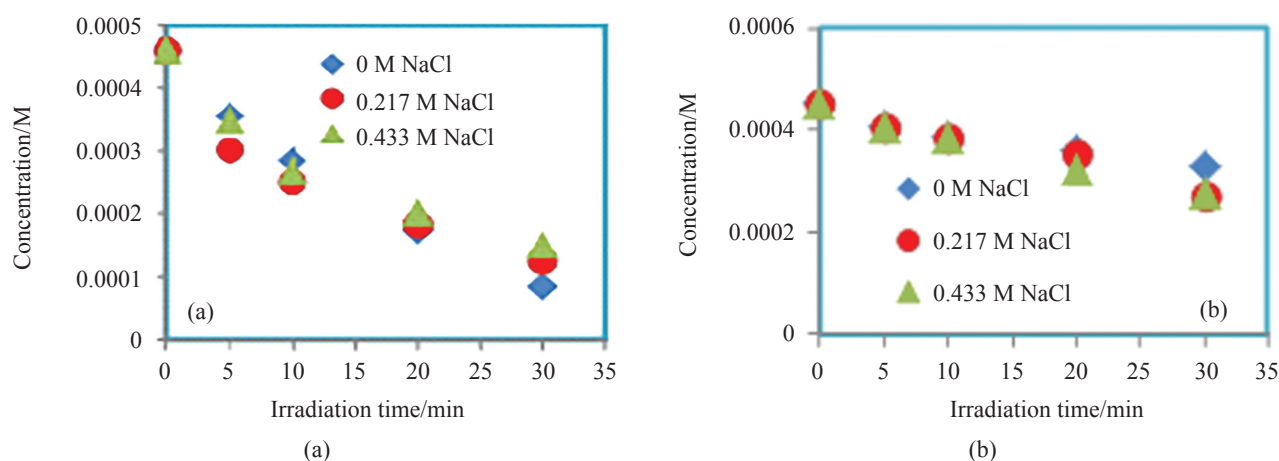
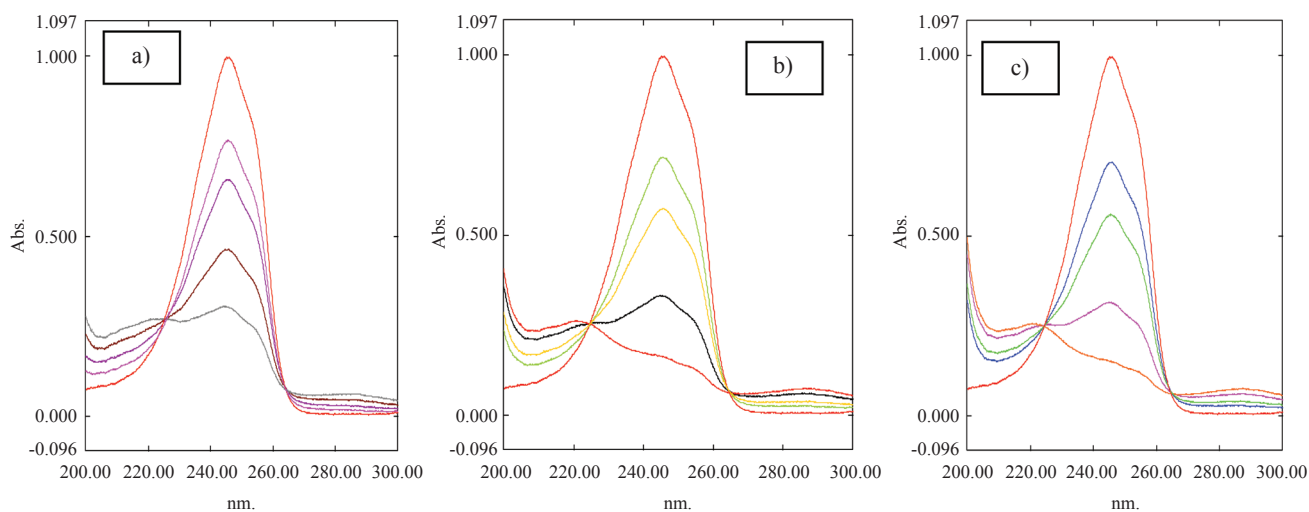FIGURE 4. Sonochemical degradation of a) 1,4-benzoquinone and b) hydroquinone in absence and presence of NaCl.

Figure 5. Time dependence of 1,4-benzoquinone sonication, isosbestic points were observed inthe absence a), in the presence of 0.217 M b) and 0.433 M c) Na$_2$SO$_4$.

atmosphere due to influence of sonolysis. It can be seen that the absorption peaks corresponding to 1,4-benzoquinone at around 245.7 nm was gradually decreased. In Figure 5, two isosbestic points were also observed at 225.6 nm and 264.5 nm, indicating that 1,4-benzoquinone certainly reduced to form hydroquinone and other compounds.

Zhao et al. (2010) studied on enhanced oxidation of 4-chlorophenol using sulfate radicals initiated from zero-valent and peroxydisulfate at ambient temperature and found sulfate radical anion as the dominant active species was responsible for the oxidation of 4-chlorophenol in the ZVI-PDS system, mechanism adopted as Equation (5).

$$SO_4^- + H_2O \rightarrow HSO_4^- + OH \tag{5}$$

INTERMEDIATES

In sonolysis of 1,4-benzoquinone and hydroquinone intermediate was detected at retention time (R.T.) 3.4 min in absence and presence of different concentrations of Na$_2$SO$_4$ and NaCl. Another intermediate was detected at retention time 10 min only for hydroquinone sonolysis.
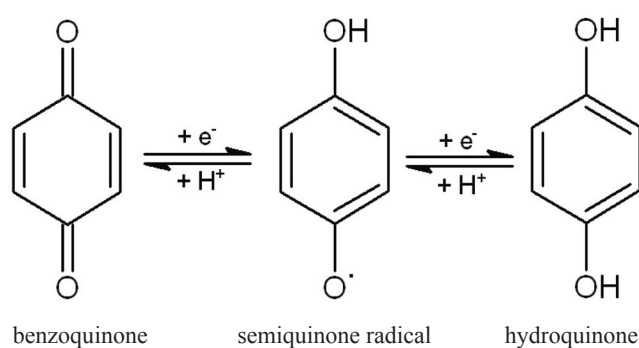

benzoquinone   semiquinone radical   hydroquinone

FIGURE 6. Reduction of 1,4-benzoquinone to the intermediate semiquinone radical and furtherreduction to hydroquinone.

Figure 7 shows the formation of intermediate at R.T. = 10.00 min for sonication of hydroquinone in absence and presence of different concentration of Na$_2$SO$_4$. The highest amount was produced in absence of Na$_2$SO$_4$ and lowest was in presence of 0.433 M Na$_2$SO$_4$. It may 1,4-benzoquinone and quantitatively measurement as shown in Figure 8. The maximum 1,4-benzoquinone was produced 15.73 μM in the absence of Na$_2$SO$_4$.
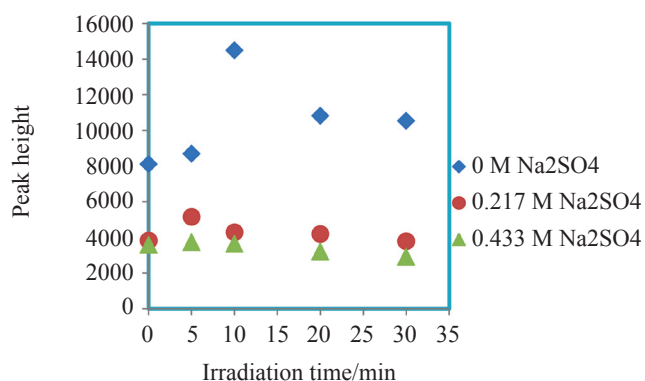
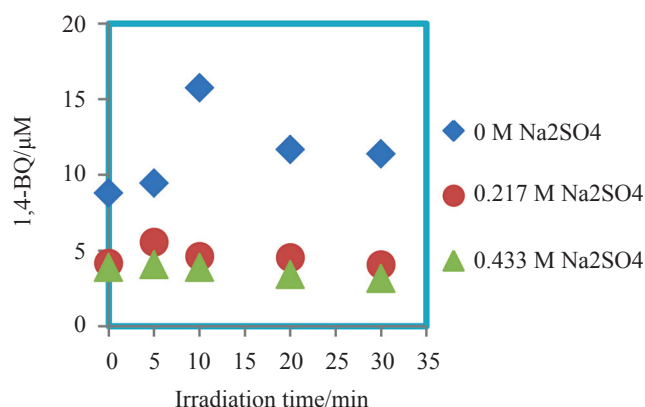FIGURE 7. Formation of intermediate at R.T. = 10.00 for sonication of hydroquinone in presence of different concentration of Na$_2$SO$_4$

FIGURE 8. Formation of 1,4-benzoquinone in hydroquinone solution at different concentration of Na$_2$SO$_4$ (Peak height).

Figure 9 shows the formation of intermediate at R.T. = 3.4 ≈ 3.7 for sonication of a) 1,4-benzoquinone, and b) hydroquinone in the absence and presence of different concentration of Na$_2$SO$_4$. The highest amount of intermediate was produced in the presence of 0.217 M Na$_2$SO$_4$. Also,

experimentally same intermediates were detected in the presence of different concentrations of NaCl. Figure 10 is indicating the reaction mechanism of 1,4-benzoquinone and hydroquinone.
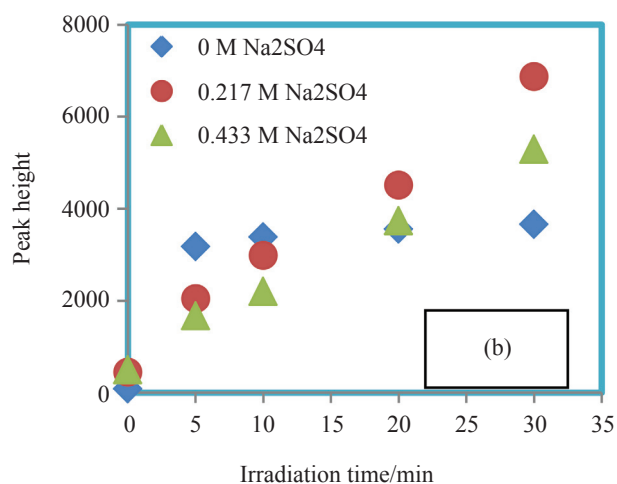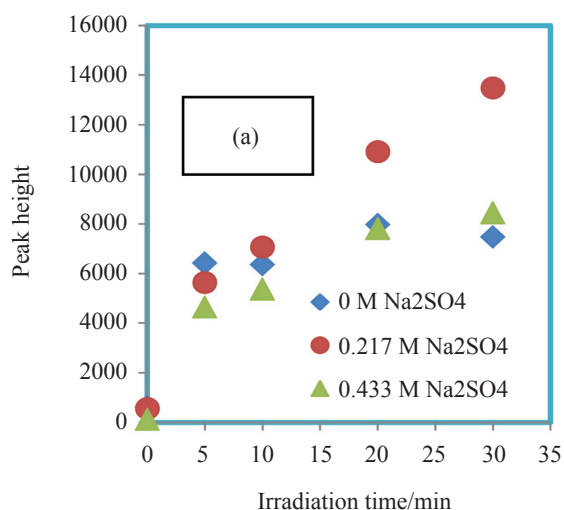

FIGURE 9. Formation of intermediate at R.T. = 3.4 ≈ 3.7 for sonication of a) 1,4-benzoquinoneand b) hydroquinone in the absence and presence of different concentration of Na$_2$SO$_4$.
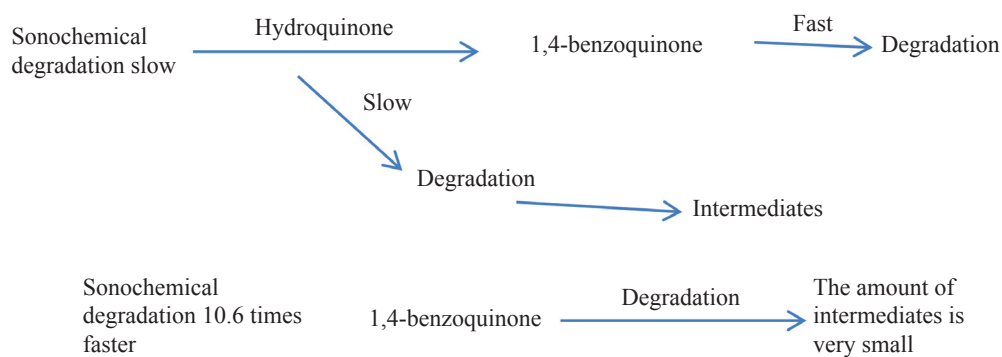

FIGURE 10. Reaction mechanism of 1,4-benzoquinone and hydroquinone

CONCLUSIONS

The effects of Na_2SO_4 and NaCl on the sonochemical degradation of 1,4-benzoquinone and hydroquinone were investigated by using 200 kHz sonicator. In absence and presence of Na_2SO_4 initial rates of sonochemical degradation were significantly increased in the order 1,4-benzoquinone > hydroquinone. Based on the experimental results, in absence of Na_2SO_4 1,4-benzoquinone sonochemical degradation rate was 4.5 times higher than hydroquinone, whereas in presence of 0.433 M Na_2SO_4 at same condition 1,4-benzoquinone reaction rate was increased 10.6 times higher than hydroquinone. On the other hand, in presence of NaCl initial rate of sonochemical degradation of 1,4-benzoquinone and hydroquinone was different. In the presence of different concentrations of NaCl the initial rate of sonochemical degradation of 1,4-benzoquinone was reduced. Also, in presence of same concentration of NaCl the initial rate of degradation of hydroquinone was no/very little effect.

REFERENCES

Anotai, J., Ming-Chun, L. & Parichat, C. 2006. Kinetics of aniline degradation by Fenton and electro-Fenton processes. *Water Research* 40(9): 1841-1847.

Ashokkumar, M., 2008. Advanced wet-chemical synthetic approaches to inorganic nanostructures, *Transworld Research Network: Kerala*, 107-131.

Ashokkumar, M. & Grieser, F. 2 004. Single bubble sonoluminescence -A chemist's overview. *Chem. Phys. Chem* 5: 439-448.

Bandala, E. R., Miguel, A. P., Dionysios, D.D., Silvia, G., Javier, G. & Diana, M. 2007. Degradation of 2, 4-dichlorophenoxyacetic acid (2, 4-D) using cobalt-peroxymonosulfate in Fenton-like process. *Journal of Photochemistry and Photobiology A: Chemistry* 186(2-3): 357-363.

Berlan, J., Trabelsi, F., Delmas, H., Wilhelm, A. M. & Petrignani, J. F. 1994. Oxidative degradation of phenol in aqueous media using ultrasound. *Ultrasonics Sonochemistry* 1(2): S97-S102.

Bilimoria, M. H. 1975. The detection of mutagenic activity of chemicals and tobacco smoke in a bacterial system. *Mutation Research/Environmental Mutagenesis and Related Subjects* 31(5): 328.

Bailey, S. I. & Ritchie, I. M. 1985. A cyclic voltammetric study of the aqueous electrochemistry of some quinones. *Electrochimica Acta* 30(1): 3-12.

Cheng, J., Chad, D. V., Hyunwoong, P., Brian, T. M. & Michael, R. H. 2009. Sonochemical degradation of perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) in groundwater: kinetic effects of matrix inorganics. *Environmental Science & Technology* 44(1): 445-450.

Dükkancı, M. & Gündüz, G. 2006. Ultrasonic degradation of oxalic acid in aqueous solutions. *Ultrasonics Sonochemistry* 13(6): 517-522.

Entezari, M. H., Christian, P. & Pierre, D. 2003. Sonochemical degradation of phenol in water: a comparison of classical equipment with a new cylindrical reactor. *Ultrasonics Sonochemistry* 10(2): 103-108.

Fernandez, J., Pichai, M., Albert, R. & John, K. 2004. Bleaching and photobleaching of Orange II within seconds by the oxone/Co2+ reagent in Fenton-like processes. *Applied Catalysis B: Environmental* 49(3): 207-215.

Guo, W.-Q., Jie, D., Guang-Li, C., Nan-Qi, R. & Fu-Yi, C. 2011. Treatability study of using low frequency ultrasonic pretreatment to augment continuous biohydrogen production. *International Journal of Hydrogen Energy* 36(21): 14180-14185.

Guo, W.-Q., Shan-Shan, Y., Wen-Sheng, X., Xiang-Jing, W. & Nan-Qi, R. 2013. Minimization of excess sludge production by in-situ activated sludge treatment processes-A comprehensive review. *Biotechnology Advances* 31(8): 1386-1396.

Hori, H., Ari, Y., Etsuko, H., Sachi, T., Nobuyoshi, Y., Shuzo, K., Hiroshi, K. & Ryuichi, A. 2005. Efficient decomposition of environmentally persistent perfluorocarboxylic acids by use of persulfate as a photochemical oxidant. *Environmental Science & Technology* 39(7): 2383-2388.

He, J., Tian, W., Guangming, Z. & Jing, Y. 2011. Ultrasonic reduction of excess sludge from activated sludge system: Energy efficiency improvement via operation optimization. *Ultrasonics Sonochemistry* 18(1): 99-103.

Henglein, A. & Kormann, C. 1985. Scavenging of OH radicals produced in the sonolysis of water. *International Journal of Radiation Biology and Related Studies in Physics, Chemistry and Medicine* 48(2): 251-258.

Jyothi, K. P., Suguna, Y. & Yesodharan, E. P. 2014. Ultrasound (US), Ultraviolet light (UV) and combination (US+ UV) assisted semiconductor catalysed degradation of organic pollutants in water: Oscillation in the concentration of hydrogen peroxide formed in situ. *Ultrasonics Sonochemistry* 21(5): 1787-1796.

Joseph, C. G., Gianluca, L. P., Awang, B., Yun, H. T.-Y. & Duduku, K. 2011. Operating parameters and synergistic effects of combining ultrasound and ultraviolet irradiation in the degradation of 2, 4, 6-trichlorophenol. *Desalination* 276(1-3): 303-309.

Joschek, H-I. & Sidney, I. M. 1966. Photooxidation of phenol, cresols, and dihydroxybenzenes1, 2. *Journal of the American Chemical Society* 88(14): 3273-3281.

Kawamukai, M. 2002. Biosynthesis, bioproduction and novel roles of ubiquinone. *Journal of Bioscience and Bioengineering* 94(6): 511-517.

Khachatryan, L., Julien, A., Zofia, M. & Barry, D. 2006. Formation of cyclopentadienyl radical from the gas-phase pyrolysis of hydroquinone, catechol, and phenol. *Environmental Science & Technology* 40(16): 5071-5076.

Lim, M., Younggyu, S. & Jeehyeong, K. 2014. The effects of hydrogen peroxide on the sonochemical degradation of phenol and bisphenol A. *Ultrasonics Sonochemistry* 21(6): 1976-1981.

Leighton, P. A. & George, S. F. 1929. The photochemical decomposition of benzoquinone in water and in alcohol. *Journal of the American Chemical Society* 51(12): 3549-3559.

Lente, G. & James, H. E. 2004. Photoreduction of 2, 6-dichloroquinone in aqueous solution: Use of a diode array spectrophotometer concurrently to drive and detect a photochemical reaction. *Journal of Photochemistry and Photobiology A: Chemistry* 163(1-2): 249-258.

Lee, M-R., Jsuey, J., Wei-Shin, H. & Bao-Huey, H. 1999. Determination of pyrolysis products of smoked methamphetamine mixed with tobacco by tandem mass spectrometry. *Journal of Analytical Toxicology* 23(1): 41-45.

Leanderson, P. & Christer, T. 1992. Cigarette smoke-induced DNA damage in cultured human lung cells: role of hydroxyl radicals and endonuclease activation. *Chemico-biological Interactions* 81(1-2): 197-208.

Ledesma, E. B., Nathan, D. M., Alyssa, K. S. & Mary, J. W. 2002. An experimental study on the thermal decomposition of catechol. *Proceedings of the Combustion Institute* 29(2): 2299-2306.

Makino, K., Magdi, M. M. & Peter, R. 1983. Chemical effects of ultrasound on aqueous solutions. Formation of hydroxyl radicals and hydrogen atoms. *The Journal of Physical Chemistry.* 87(8): 1369-1377.

Mallakpour, S., Maryam, M. & Sahar, R. 2014. Applications of ultrasound for modification of zinc oxide and fabrication of optically active poly (amide-imide)/zinc oxide bionanocomposites. *Designed Monomers and Polymers* 17(4): 364-371.

Marsh, N. D., Elmer, B. L., Alyssa, K. S. & Mary J. W. 2004. Yields of Polycyclic Aromatic Hydrocarbons from the Pyrolysis of Catechol [ortho-Dihydroxybenzene]: Temperature and Residence Time Effects. *Energy & Fuels* 18(1): 209-217.

Mason, T. J. 1991. *Practical Sonochemistry: User's Guide to Applications in Chemistry and Chemical Engineering.* Ellis Horwood.

Moret, E. E., Mark, de-B., Hans, W. H., Jan, P. T., Lambert, H. M. J., Joost, J. M. H., Reinoud, J. D., Willem, V. & David, N. R. 1996. In vivo activity and hydrophobicity of cytostatic aziridinyl quinones. *Journal of Medicinal Chemistry* 39(3): 720-728.

Nanzai, B., Kenji, O., Norimichi, T., Hiroshi, B. & Yasuaki, M. 2008. Sonochemical degradation of various monocyclic aromatic compounds: Relation between hydrophobicities of organic compounds and the decomposition rates. *Ultrasonics Sonochemistry* 15(4): 478-483.

Nurmi, J. T. & Paul, G. T. 2002. Electrochemical properties of natural organic matter (NOM), fractions of NOM, and model biogeochemical electron shuttles. *Environmental Science & Technology* 36(4): 617-624.

Okamura, M. Y., Paddock, M. L., Graige, M. S. & Feher, G. 2000. Proton and electron transfer in bacterial reaction centers. *Biochimica et Biophysica Acta (BBA)-Bioenergetics* 1458(1): 148-163.

Okitsu, K., Akihiko, Y., Shuji, T., Hiroshige, M., Yoshihiro, Y. & Youngeok, Y. 2002. Sonolytic control of rate of gold (III) reduction and size of formed gold nanoparticles: relation between reduction rates and sizes of formed nanoparticles. *Bulletin of the Chemical Society of Japan* 75(10): 2289-2296.

Petrier, C., Marie-Francoise, L., Anne, F., Abdallah, B., Bernard, D., Viviane, R. & Nicolas, G. 1994. Sonochemical degradation of phenol in dilute aqueous solutions: comparison of the reaction rates at 20 and 487 kHz. *The Journal of Physical Chemistry* 98(41): 10514-10520.

Patnaik, P. 2007. *A Comprehensive Guide to the Hazardous Properties of Chemical Substances.* John Wiley & Sons.

Paterová, J., Kelvin, B. R., Jan, H., Yadagiri, K., Halil, I. O., Wenshe, R. L., Christian, H., Paul, S. C. & Pavel, J. 2013. Reversal of the Hofmeister series: specific ion effects on peptides. *The Journal of Physical Chemistry B* 117(27): 8150-8158.

Rosenfeldt, E. J. & Karl, G. L. 2004. Degradation of endocrine disrupting chemicals bisphenol A, ethinyl estradiol, and estradiol during UV photolysis and advanced oxidation processes. *Environmental Science & Technology* 38(20): 5476-5483.

Riesz, P., Berdahl, D. & Christman, C. L. 1985. Free radical generation by ultrasound in aqueous and nonaqueous solutions. *Environmental Health Perspectives* 64: 233-252.

Rokhina, E. V., Katerina, M., Manu, L., Elena, A. G., Henk, V. A. & Jurate, V. 2013. Ultrasound-assisted MnO_2 catalyzed homolysis of peracetic acid for phenol degradation: The assessment of process chemistry and kinetics. *Chemical Engineering Journal* 221: 476-486.

Spanggord, R. J., David, Y. & Theodore, M. 2000. Kinetics of aminodinitrotoluene oxidations with ozone and hydroxyl radical. *Environmental Science & Technology* 34(3): 450-454.

Saccani, G., Bernasconi, M. & Antonelli, M. 2014. Optimization of low energy sonication treatment for granular activated carbon colonizing biomass assessment. *Environmental Technology* 35(7): 851-858.

Sakakura, M. & Mitsuo, T. 2012. Improved sonolytic hydrolysis of peptides in aqueous solution with addition of 1, 4-benzenedithiol. *Ultrasonics Sonochemistry* 19(3): 615-620.

Serpone, N., Terzian, R., Colarusso, P., Minero, C., Pelizzetti, E. & Hidaka, H. 1993. Sonochemical oxidation of phenol and three of its intermediate products in aqueous

media: catechol, hydroquinone, and benzoquinone. Kinetic and mechanistic aspects. *Research on Chemical Intermediates* 18(2): 183-202.

Spyroudis, S. 2000. Hydroquinones: synthesis and reactivity. *Molecules* (5): 1291-1330.

Sakai, T. & Masayuki, H. 1976. Thermal decarbonylation of catechol, hydroquinone and resolsinol. *Chemistry Letters* 5(11): 1153-1156.

Scott, D. T., Diane, M. M., Elizabeth, L. B-H., Sarah, E. K. & Derek, R. L. 1998. Quinone moieties act as electron acceptors in the reduction of humic substances by humics-reducing microorganisms. *Environmental Science & Technology* 32(19): 2984-2989.

Topping, D. C., Lisa, G. B., John, L. O'D. & Caroline, E. J. 2007. Hydroquinone: acute and subchronic toxicity studies with emphasis on neurobehavioral and nephrotoxic effects. *Food and Chemical Toxicology* 45(1): 70-78.

Torres-Palma, R.A., Nieto, J.I., Combet, E., Petrier, C. & Pulgarin, C., 2010. An innovative ultrasound, Fe2+ and TiO2 photoassisted process for bisphenol a mineralization. *Water Research* 44(7): 2245-2252.

Uddin, M. H., Ben, N. & Kenji, O. 2016. Effects of Na_2SO_4 or NaCl on sonochemical degradation of phenolic compounds in an aqueous solution under Ar: Positive and negative effects induced by the presence of salts. *Ultrasonics Sonochemistry* 28: 144-149.

Verma, A., Harmanpreet, K. & Divya, D. 2013. Photocatalytic, sonolytic and sonophotocatalytic degradation of 4-chloro-2-nitro phenol. *Archives of Environmental Protection* 39(2): 17-28.

Visser, R., Harbers, A. A. M., Hovestad, A. & Stevens, T. W. 1985. Identification of organic compounds in waste water of wood gasifiers with capillary gas chromatography. In *Proceedings of the 6th International Symposium on Capillary Chromatography*, 281-287.

Veith, G. D., Austin, N. M. & Morris, R. T. 1979. A rapid method for estimating log P for organic chemicals. *Water Research* 13(1): 43-47.

Waldemer, R. H., Paul, G. T., Richard, L. J. & James, T. N. 2007. Oxidation of chlorinated ethenes by heat-activated persulfate: kinetics and products. *Environmental Science & Technology* 41(3): 1010-1015.

Wang, R.-C. & Chih-Wen, Y. 2013. Phenol degradation under visible light irradiation in the continuous system of photocatalysis and sonolysis. *Ultrasonics Sonochemistry* 20(1): 553-564.

Yang, S.-S., Wan-Qian, G., Guang-Li, C., He-Shan, Z. & Ren, N. Q. 2012. Simultaneous waste activated sludge disintegration and biological hydrogen production using an ozone/ultrasound pretreatment. *Bioresource Technology* 124: 347-354.

Yang, S.-S., Wan-Qian, G, Zhao-Hui, M., Xian-Jiao, Z., Xiao-Chi, F., He-Shan, Z., Bo, L., Nan-Qi, R. & Ya-Shan, C. 2013. Characterizing the fluorescent products of waste activated sludge in dissolved organic matter following ultrasound assisted ozone pretreatments. *Bioresource Technology* 131: 560-563.

Yim, B., Youngeok, Y., & Yasuaki, M. 2003. Sonolysis of alkylphenols in aqueous solution with Fe (II) and Fe (III). *Chemosphere* 50(8): 1015-1023.

Zhang, K., Naiyun, G., Yang, D., Tsair, F. L., Yan, M., Lei, L. & Minghao, S. 2011. Degradation of bisphenol-A using ultrasonic irradiation assisted by low-concentration hydrogen peroxide. *Journal of Environmental Sciences* 23(1): 31-36.

Zhao, J., Yaobin, Z., Xie, Q. & Shuo, C. 2010. Enhanced oxidation of 4-chlorophenol using sulfate radicals generated from zero-valent iron and peroxydisulfate at ambient temperature. *Separation and Purification Technology* 71(3): 302-307.

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