

Original Research Article

Ultrasound Assisted Sonochemical Decomposition of Methyl Orange in the Presence of H₂O₂ and CCl₄

ABSTRACT

Methyl orange (MO) is an orange azoic dye; which has transition range from 3.1 to 4.4. Sonochemical decomposition of methyl orange in the presence of H₂O₂ and CCl₄ has given effective result to reclaim water from the effluents released by the industries. The aim of this research was to investigate the effective condition for the decomposition of MO in the presence or absence of additives. For this, 50 mg/L solution of MO was sonicated in the presence and absence of different additives. It was clearly confirmed that the rates of sonochemical decomposition of MO increased with increasing the concentration in both cases of H₂O₂ and CCl₄. The combination of advanced oxidation processes (AOPs) namely hydrogen peroxide and carbon tetra-chloride with sonolysis harvests the decomposition of wide spectrum of organic contaminants. The combination of sonolysis with H₂O₂ and CCl₄ enhances the production of non-selective radicals to improve the decomposition process. The AOPs is technically feasible and also economic. Based on the results, it was suggested that the rate of MO decomposition can be effectively enhanced by the sonolysis of CCl₄ and also for H₂O₂. It was possible to include order- MO+200μL H₂O₂ > MO+100μL H₂O₂ > MO+20μL H₂O₂ > MO; MO+200μL CCl₄ > MO+100μL CCl₄ > MO+20μL CCl₄ > MO.

Keywords: Methyl orange; sonolysis; radical reaction.

1. INTRODUCTION

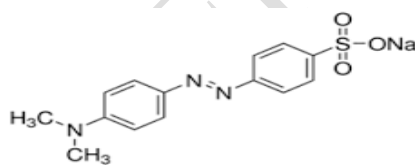
Energy, food and water are interconnected & within the nation, water is essential for all social and economic developments. In the oncoming years, worldwide crisis may arise for energy, food, and water [1]. The percentage of increasing in concentration of organic contaminants in surface water has been observed by the past two decades [2, 3]. The removal of hazardous substances from industrial waste streams and the process of remediation of contaminants in groundwater, rock and soil is a major problem in the Asian countries [4]. As diseases spread through water which becomes unsuitable for usages in day to day life in human beings, for the usages of polluted water, water borne diseases spread throughout the world and in the awkward case, it causes the mortality of children [5, 6].

Contamination of soil and groundwater from industrial waste streams is a serious health problem. Traditional techniques to remove contaminants from soil: including landfilling, air stripping/carbon adsorption, incineration, biological activity and chemical treatment. Incineration, adsorption and landfilling merely transfer the contaminant to another phase or location (i.e., a pollution shift) and produce a potentially dangerous and toxic secondary disposal requirement. To numerous environmental factors biodegradation is very sensitive, is slow, produces unpredictable results often, and is uneconomical for highly concentrated waste effluents. Current developments in environmental technologies involving chemical oxidation have the potential to treat all types of organic and inorganic contaminants (volatile,

50 semi-volatile and non-volatile). Those processes, which all are oxygen based, are usually
 51 termed as advanced oxidation processes (AOPs).

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 53 An AOPs can define as the oxidation process that generally generates hydroxyl radicals in
 54 sufficient quantity to affect water treatment. Complete mineralization can be entailed by the
 55 oxidative processes, implying that the final products of degradation reactions are carbon
 56 dioxide, short-chain organic acids, and inorganic ions, typically less toxic and favorable to
 57 biodegradation. The AOPs generally use a combination of oxidation agents (O_3 , H_2O_2),
 58 irradiation (ultraviolet, ultrasound) and catalysts (TiO_2) as a means of generating the excited
 59 hydroxyl or hydroxyl radicals, which are more powerful oxidants than molecular O_3 or H_2O_2
 60 [7-17].

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 62 Recent advances in AOPs include environmental sonochemistry, which involves the
 63 application of ultrasound to induce in situ cavitation to destroy or accelerate the destruction
 64 of liquid-phase contaminants [18, 19]. Some reactions involved in AOPs are found in Table 1
 65 [20, 21]. Cavitation is the nucleation, growth, and sudden collapse of gas or vapor-filled
 66 micro-bubbles formed from acoustical wave-induced compression or refraction in a body of
 67 liquid [19]. The number of reacted molecules per unit of ultrasonic energy is marked as the
 68 sonochemical efficiency value. For hazardous organic dye the degradation of methyl orange
 69 used as model in the presence of additives such as H_2O_2 , CCl_4 was carried out. Because
 70 methyl orange (MO) is a pH indicator and due to its clear color change it is very often used in
 71 titrations. MO changes color at the pH of a mid-strength acid and is usually used in titrations
 72 for acids. Unlike a so called universal indicator, MO does not have a full spectrum of color
 73 change, but has a sharper end point. The structure of the MO can be observed in Figure 1.



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 80 **Figure 1.** Structure of methyl orange.

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 83 **Table 1.** Some reactions involved in advanced oxidation processes.

Sonolysis	$H_2O +))) \rightarrow \cdot OH + OH^-$ $H_2O +))) \rightarrow (1/2)H_2 + (1/2)H_2O_2$
Fenton reactions	$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + \cdot OH + OH^-$
Sonophotocatalysis (with H_2O_2)	$H_2O +))) \rightarrow \cdot OH + OH^-$ $H_2O +))) \rightarrow (1/2)H_2 + (1/2)H_2O_2$
(a) Water sonolysis	
(b) Reaction of H_2O_2 with H atoms (formed from water sonolysis)	$H_2O_2 + H \rightarrow \cdot OH + H_2O$
(c) Photolytic dissociation of H_2O_2	$H_2O_2 + h\nu \rightarrow 2 \cdot OH$
(d) Reaction of H_2O_2 with superoxides (formed in the presence of TiO_2 and under UV radiation)	$H_2O_2 + O_2^- \rightarrow \cdot OH + OH^- + O_2$
(e) Reaction of H_2O_2 with electrons (conduction band electrons are generated from semi-conductor photocatalyst under UV irradiation).	$H_2O_2 + e^- \rightarrow \cdot OH + OH^-$ $O_3 + \cdot OH \rightarrow \cdot OH$ $UV + H_2O_2 + O_3$
Ozone + sonolysis	$H_2O +))) \rightarrow \cdot OH + OH^-$ $H_2O +))) \rightarrow (1/2) H_2 + (1/2)$

	$\text{H}_2\text{O}_2 + \text{O}_3 \rightarrow \text{O}_2(\text{g}) + \text{O} (^3\text{P})(\text{g})$ $\text{O} (^3\text{P})(\text{g}) + \text{H}_2\text{O}(\text{g}) \rightarrow 2 \cdot\text{OH}$
Semiconductor photo-catalysis (TiO ₂ -Semiconductor)	$\text{TiO}_2 + h\nu \rightarrow \text{TiO}_2^- + \cdot\text{OH} \text{ (or } \text{TiO}_2^+)$ $\text{TiO}_2^- + \text{O}_2 + \text{H}^+ \rightarrow \text{TiO}_2 + \text{H}_2\text{O} + \cdot\text{OH}$ $\text{TiO}_2^- + 2\text{H}^+ \rightarrow \text{TiO}_2 + \text{H}_2$ $\text{H}^+ + \text{H}_2\text{O} \rightarrow \cdot\text{OH} + \text{H}^+$

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86 **1.1 Fundamental Theory of Sonochemistry:**

87 The study of sonochemistry is concerned with understanding the effect of sonic waves
88 and wave properties on chemical systems. The chemical effects of ultrasound do not come
89 from a direct interaction with molecular species. Studies have shown that no direct coupling
90 of the acoustic field with chemical species on a molecular level can account for
91 sonochemistry or sonoluminescence. Instead, sonochemistry arises from acoustic cavitation:
92 the formation, growth, and implosive collapse of bubbles in a liquid. This is demonstrated in
93 phenomena such as ultrasound, sonication, sonoluminescence, and sonic cavitation. The
94 attractiveness of sonochemistry in environmental engineering seems to stem from three major
95 facts.

96 Firstly, sonochemistry can cause real chemical changes to a solution without the necessity of
97 adding any other compounds. Secondly, sonochemistry is often conducted at low or ambient
98 temperatures and pressures; thus, no heating or pressurization is required. These two features
99 simplify enormously the design and operation of reactors. Thirdly, in many cases, the
100 peculiar nature of sonochemical reactions offers alternative pathways, providing a faster or
101 environmentally safer degradation of contaminants. Some sonochemical syntheses have also
102 been successfully scaled up to plant size, providing convenient advantages such as lower
103 operation costs and shorter times of operation compared to traditional techniques. The present
104 challenge for sonochemists and acoustical physicists in the field of environmental
105 remediation is to provide cost-effective sonochemical solutions to large-scale problems.
106 Sonochemistry proceeds because the passing of acoustical waves of large amplitude, called
107 finite amplitude waves, through solutions causes cavitation. Cavitation can be generated
108 when large pressure differentials are applied in a flowing liquid (hydro dynamical cavitation),
109 or by means of an electromechanical transducer, piezo electrical or magnetostrictive, in
110 contact with the fluid (acoustical cavitation) according to Figure 2.

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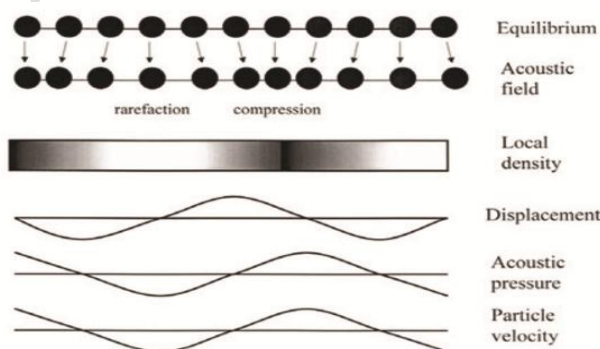
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122 **Figure 2:** Propagation of a one-dimensional ultrasound wave [C.E. Brennen et al.
123 *Journal of fluid mechanics*, **355** (1998) 255-283].

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125 The aim of this research was to investigate the effective condition for the decomposition of
126 MO in the presence or absence of additives. In addition, was to make comparison the

127 percentage of dye molecule degradation on ultrasound with and without additives such as
 128 H_2O_2 , CCl_4 at room temperature will be made.

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130 2. EXPERIMENTAL METHODOLOGY

131 Hydrogen peroxide, methyl orange and carbon tetrachloride were purchased from Merck
 132 KGaA 64271 Darmstadt, Germany. All the chemicals were reagent grade and used as received.
 133 An ultrasonicator model soniclean 250HT, 50-60 Hz was used to decompose dye molecule in
 134 aqueous medium. The schematic diagram of the experimental setup to shown in the Figure 3.
 135 A conical flask with a total volume of 100 mL of 50 mg/L sample solution was used for
 136 ultrasonic irradiation under air at room temperature around 24°C . The sonicated solution was
 137 extracting every (0, 3, 7 and 10 min) by a glass syringe (1 mL) without exposing the sample
 138 to air. The glass vessel was flat bottomed and was mounted at a constant position (4.0 mm
 139 from the oscillator). The sonicated solutions were analysed by a UV-Vis spectrophotometer
 140 (Shimadzu UV-1650).

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Figure 3: Schematic diagram of the experimental set-up.

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161 2.1 Calorimetrically Measurement of Temperature Change with Sonication Time:

162 A technique for quantitatively evaluating an ultrasonic reaction field has been investigated.
 163 Ultrasonic power is one of the important factors for sonochemistry. Calorimetry is one of the
 164 most frequently used methods for measuring the actual ultrasonic power input for a solution.
 165 Equation (1) gives the calculated ultrasonic output power (P).

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$$P = (dT/dt) C_p M \quad \text{----- (1)}$$

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Where,

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C_p is heat capacity of water (4.178 kJ/mole)

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M is mass of water (100 gm)

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dT is temperature of the sample solution ($^\circ\text{C}$)

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dt is ultrasonic irradiation time/s.

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Table 2. Measurement of temperature change during sonication:

	Sonication	Initial	Final	Temperature	Actual
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Observation	time (sec)	temperature (°C)	temperature (°C)	change (°C)	power (Watt)
1	30	24.7	25.0	0.3	4.180
2	60	25.0	25.4	0.4	2.787
3	90	25.4	25.9	0.5	2.322
4	120	25.9	26.5	0.6	2.090
5	150	26.5	27.2	0.7	1.951
6	180	27.2	28	0.8	1.858

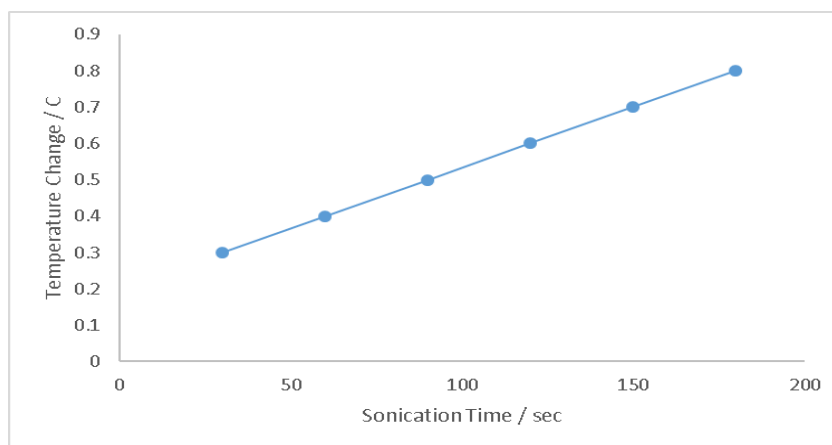


Figure 4: The change of temperature with increasing sonication time.

3. RESULTS AND DISCUSSION

3.1 Sonochemical Decomposition of Methyl Orange:

Sonication experiments were conducted with Methyl Orange solutions to study the decomposition of 50 mg/L dye solution at room temperature. Figure 5 represents the effect of sonolytic decomposition of MO in aqueous solution.

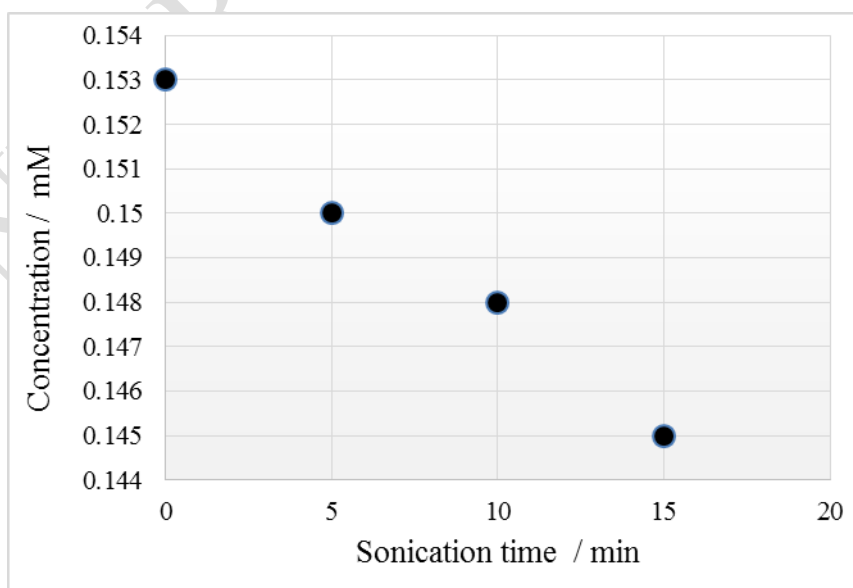


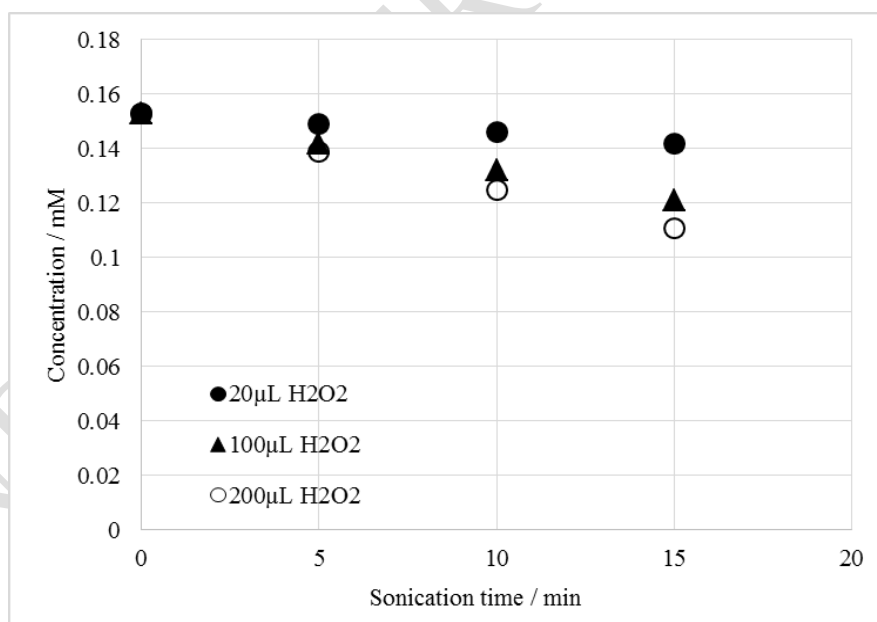
Figure 5: Sonochemical decomposition of methyl orange in the absence of additives.

203 As it can be seen from Figure 5, the concentration of MO decreased gradually as the
 204 sonication time increased. So, it can be said that, MO degrades gradually with the increase in
 205 sonication time. When no sonication occurred the concentration of MO was 0.153 mM. After
 206 sonicating for 5, 10 and 15min, the concentration decreased gradually. Also, the rate constant
 207 was obtained 0.003.

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209 a) **Sonochemical Decomposition of Methyl Orange in Presence of Different**
 210 **Concentration of H₂O₂:**

211 One of the most popular advanced oxidation processes (AOPs) methods for decomposition of
 212 organic compounds is the oxidation with H₂O₂. In the presence of H₂O₂ is a key parameter
 213 for dye decomposition in AOPs technique, depending on its concentration and nature of
 214 reductants H₂O₂ increase the formation rate of hydroxyl radicals in two ways. Firstly, the
 215 reduction of H₂O₂ at the conduction band would produce hydroxyl radicals. Secondly, the
 216 self-decomposition as a result of ultrasound irritation would also produce hydroxyl radicals.
 217 Generally, the decolorization rate of dye increases as the H₂O₂ concentration increases until
 218 an optimal concentration is achieved [22]. Recently, ultrasound irradiation was described as a
 219 possible generation of highly active [•]OH, HOO[•] and H[•] radicals [23]. However, at high
 220 concentration, H₂O₂ can also become a scavenger of valence bond holes and [•]OH radicals
 221 causing less dye to be degraded. The effect of ultrasonic irradiation combined with H₂O₂ is
 222 observed only when free radical attack is the controlling mechanism. In order to investigate
 223 the effect induced from the addition of different concentration of H₂O₂, the sonolytic
 224 degradation of 100mL of MO solution was performed. The concentration of H₂O₂ used are
 225 20 μ L, 100 μ L, and 200 μ L of H₂O₂ solution. These results are illustrated in Figure 6.
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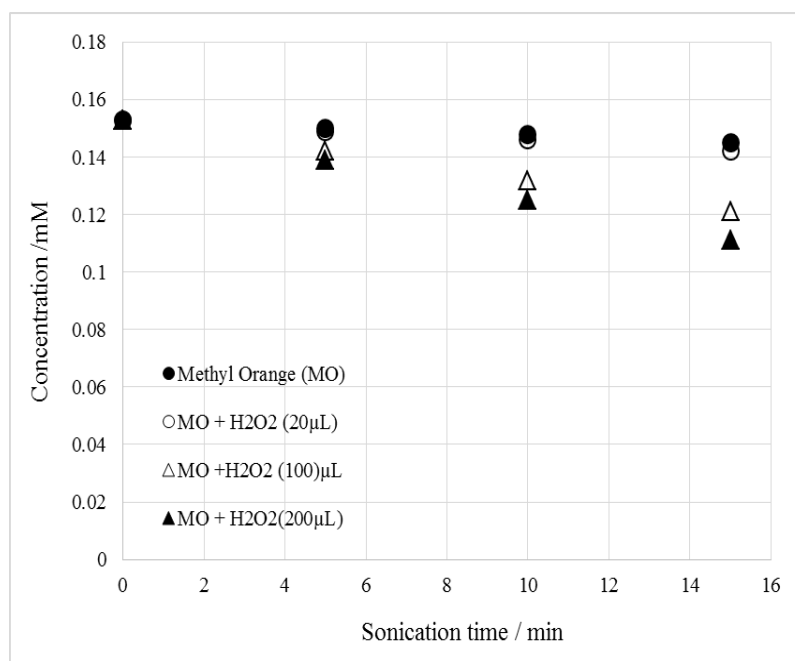
229 **Figure 6:** Sonochemical decomposition of methyl orange in the presence of different
 230 concentrations of H₂O₂.

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232 b) **Comparison of Sonochemical Decomposition of Methyl Orange (MO) with and**
 233 **without Different Concentrations of H₂O₂:**

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235 In the presence of ultrasound, the decomposition of MO without H₂O₂ increased. But when
 236 H₂O₂ added to the solution of MO, it enhances the rate of decomposition of MO. The higher
 237 the concentration H₂O₂, the rate of decomposition of MO also increases Figure 7.
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Figure 7: Comparison of sonochemical decomposition of MO with and without different concentrations of H₂O₂.

244 According to this Figure 7 shows the increase in the concentration of H₂O₂, increasing the
 245 rate of decomposition of MO and follows the trend of sequences below; **MO + 200 µL H₂O₂**
 246 **> MO + 100 µL H₂O₂ > MO + 20µL H₂O₂ > MO.** Sonochemical decomposition of MO in the
 247 presence of different concentrations of H₂O₂ are **MO + 20µL H₂O₂ is 0.005, MO + 100µL**
 248 **H₂O₂ is 0.016 and MO + 200µL H₂O₂ is 0.021** Figure 7.

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251 c) Sonochemical Decomposition of Methyl Orange in Presence of Different 252 Concentration of CCl₄:

253 In order to investigate the effects induced from the addition of different concentration of
 254 CCl₄, the sonolytic decomposition of 100mL of MO solution was performed. Here the
 255 concentration of CCl₄ used are 20µL, 100µL and 200µL respectively. These results are
 256 illustrated in Figure 8.

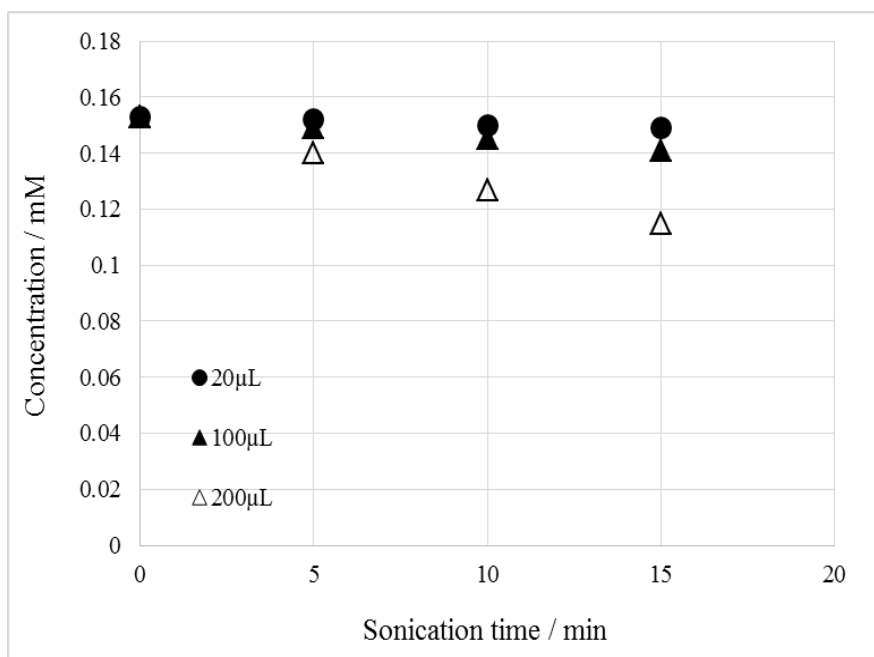
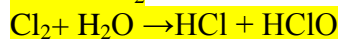
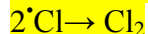
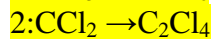
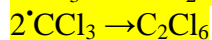
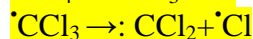


Figure-8: Sonochemical decomposition of methyl orange in the presence of different concentrations of CCl_4 .

The rate of dye decomposition increases with the increasing of concentration of CCl_4 . Recently, it has been reported that the analysis for the rate of the sonochemical decomposition of organic compounds in water can be colorimetrically performed to understand the sonochemical efficiency, where the rate of the sonochemical decomposition is suggested to be reasonably correspondent to the yield of H_2O_2 . For examples, porphyrins [24] are so far used for the model compounds. These methods would be convenient for the analysis of the sonochemical efficiency under an ultrasonic irradiation condition. Our results suggested that the sonochemical decomposition of MO in the presence of CCl_4 would be useful to evaluate the sonochemical efficiency, because the rate of the MO decomposition can be effectively enhanced by the sonolysis of CCl_4 .

d) Comparison of decomposition of Methyl Orange (MO) with & without different concentration of CCl_4 :

In this study, it was found that the rate of the MO decomposition could be enhanced by the addition of CCl_4 . This reason could be qualitatively explained by the sonochemical decomposition of CCl_4 to form various types of active species, which can react with MO molecules. It has been reported that the sonolysis of CCl_4 in water occurs as seen in Equations below [25, 26]:



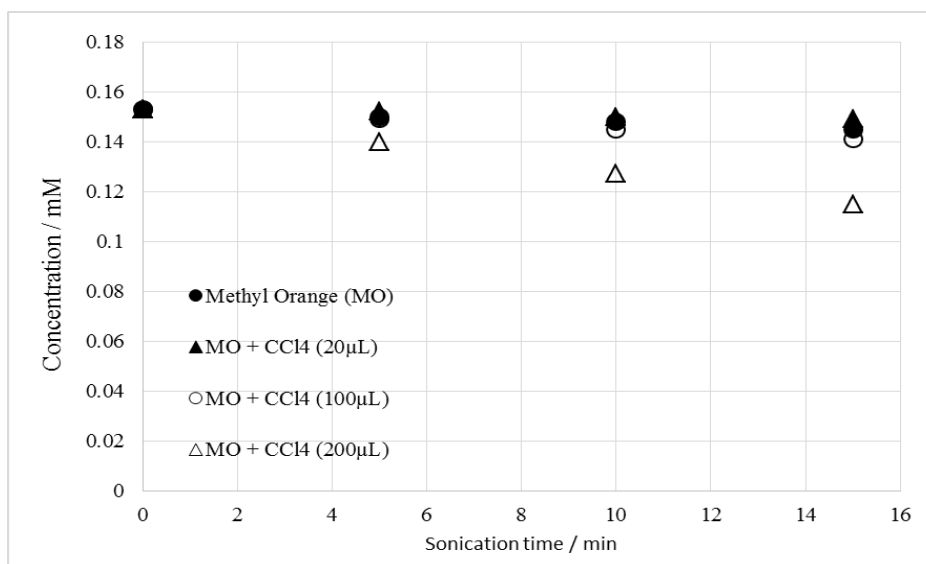


Figure-9: Comparison of sonochemical decomposition of MO with and without different concentrations of CCl₄.

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295 In the presence of ultrasound, the decomposition of MO without CCl₄ increased. But when
296 CCl₄ added to the solution of MO, it enhances the rate of decomposition of MO. The higher
297 the concentration CCl₄, the rate of decomposition of MO also increases. Based on the
298 obtained results, it was suggested that the enhancement effect was dependent on the
299 ultrasonic irradiation condition. This would be due to that the cavitation phenomenon induced
300 by ultrasonic irradiation is sensitively affected by the experimental conditions such as
301 ultrasound frequency and power, volume of solution, etc. For example, a change in the
302 ultrasound frequency may affect one or many of the following factors [24, 26, 27]: (1) the
303 temperature and pressure inside the collapsing cavitation bubbles, (2) the number and
304 distribution of bubbles, (3) the size and lifetime of bubbles, (4) the dynamics and symmetry
305 (shape) of the bubble collapse, (5) the effect of organic additive on bubble temperature, (6)
306 the effect of intermediates and products, etc. It is quite difficult to quantify the individual
307 effects of these factors, since they are interdependent and it is almost impossible to control
308 one factor without affecting the others. In addition, the rate of the decomposition would be
309 affected by the geometrical placement of the instrumental components such as the shape of
310 the reaction cell, the volume of the sample solution, the size of the used ultrasonic oscillator,
311 etc. According to, increase in concentration of CCl₄, the increasing rate of decomposition of
312 MO can be written as (Figure 9): MO+200 μL CCl₄ > MO+100 μL CCl₄ > MO+20 μL CCl₄ >
313 MO. In addition, sonochemical decomposition of MO in the presence of different
314 concentrations of CCl₄ are MO + 20 μL CCl₄ is 0.002, MO + 100 μL CCl₄ is 0.005 and MO +
315 200 μL CCl₄ is 0.019 Figure 9.

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4. CONCLUSION

320 Sonochemical decomposition of methyl orange (MO) was studied in the absence and
321 presence of different concentrations of H₂O₂ and CCl₄. MO molecule can be effectively
322 removed from water by sonolysis. This study exhibits that the sonochemical decomposition
323 occurs mainly through reactions with hydroxyl and chloride radicals. It was found that the
324 initial decomposition of MO molecule increased. But by the addition of CCl₄ and also for

325 H₂O₂, the rates of sonochemical decomposition of MO were enhanced. This process is
 326 technically feasible & also economic. Eventually reached to a conclusion. According to,
 327 increase in concentration of CCl₄, the increasing rate of decomposition of MO can be written
 328 as: MO + 200 μL CCl₄ > MO + 100 μL CCl₄ > MO + 20 μL CCl₄ > MO. Similarly for H₂O₂
 329 the increasing rate of decomposition of MO can be written as: MO + 200 μL H₂O₂ > MO +
 330 100 μL H₂O₂ > MO + 20 μL H₂O₂ > MO.

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332 **REFERENCES**

- [1] Olsson G. Water and energy: conflicts and connections. *Water* 2012;21:12-4.
- [2] Eikebrokk B, Vogt RD, Liltved H. NOM increase in Northern European source waters; discussion of possible causes & impacts on coagulation/contact filtration processes. *Water Sci Technol: Water Supply* 2004(4):47-54.
- [3] Korth A, Fiebigler C, Bornmann K, Schmidt W. NOM increase in drinking water reservoirs – relevance for drinking water production. *Water Science Technol: Water Supply* 2004(4):55-60.
- [4] Bolton, J.R. *Ultraviolet Applications Handbook*; Boltons Photoscience Inc.: Ayr, ON, Canada, 1999.
- [5] Ustun AP, Corvalan C. Preventing disease through healthy environments: towards an estimate of the environmental burden of disease. Geneva, Switzerland: WHO Publishers; 2006. p. 1-104
- [6] Batterman S, Eisenberg J, Hardin R, Kruk ME, Lemons MC, Michalak AM, et al. Sustainable control of water-related infectious diseases: a review and proposal for interdisciplinary health-based systems research. *Environ Health Perspect* 2009;117:1023-32.
- [7] Kasprzyk-Hordén, B.; Ziolk, M.; Nawrocki, J. Catalytic Ozonation & Methods of Enhancing Molecular Ozone Reactions in Water Treatment. *Appl. Catal., B* 2003, 40, 639-669.
- [8] Neyens, E.; Baeyens. A Review of Classic Fenton's Peroxidation as an Advanced Oxidation Technique. *J. Hazard. Mater.* 2003, B98, 33-50.
- [9] *Chemical Degradation Methods for Wastes & Pollutants: Environmental & Industrial Applications*; Tarr, M. A., Ed.; Marcel Dekker: New York, 2003.
- [10] Bolton, J.R. *Ultraviolet Applications Handbook*; Boltons Photoscience Inc.: Ayr, ON, Canada, 1999.
- [11] Ollis, D.F.; Pelizzetti, E.; Serpone, N. Photocatalyzed Destruction of Water Contaminants. *Environ. Sci. Technol.* 1991, 25, 1523-1529.
- [12] R. Venkatadri and R. W. Peters, "Chemical oxidation technologies: ultraviolet light/hydrogen peroxide, Fenton's reagent, and titanium dioxide-assisted photocatalysis," *Hazardous Waste and Hazardous Materials*, vol. 10, no. 2, pp. 107–149, 1993.
- [13] Kasprzyk-Hordén, B.; Ziolk, M.; Nawrocki, J. *Appl. Catal. B* 2003, 40, 639-669.
- [14] Hoffmann, M.R.; Hua, I.; Hochemer. R. *Ultrason. Sonochem.* 1996, 3, S163-S172.
- [15] Jain, V. K. *Environ. Sci. Technol.* 1993, 27, 806-808.
- [16] Shaw, R.W; Brill, T. B.; Clifford, A.A.; Eckert, C A.; Franck, E. U. *Chem. Eng. News* 1991, December, 23-35.
- [17] Thomson, T. B.; Modell, M. *Hazard. Waste.* 1984, 4, 453-467.
- [18] Adewuyi, Y. G. *Sonochemistry: Environmental Science & Engineering Applications. Ind. Eng. Chem. Res.* 2001, 40, 4681-4715.
- [19] Ince, N. H.; Tezcanli, G.; Belen, R.K.; Apikyan, I. G., *Appl. Catal., B* 2001, 29, 167-176.
- [20] Joseph CG, Puma GL, Bono A, Krishnaiah D. Sonophotocatalysis in advanced

- oxidation process; a short review . *Ultrason sonochem.* 2009; 16: 583-90.
- [21] Ince, N. H.; Tezcanli, G.; Belen, R.K.; Apikyan, I. G., *Appl. Catal., B* 2001,49:145-53.
- [22] N.M. Mahmoodi, M. Arami, N. Yousefi Limaee, N. Salman Tabrizi, Decolorization & aromatic ring degradation kinetics of Direct Red 80 by UV oxidation in the presence of H₂O₂ utilizing TiO₂ as a photo-catalyst , *Chem. Eng. J.* 112(2005) 191-196.
- [23] K.S. Suslik, *Sonochemistry, Science* 247 (1990) 1439-1445.
- [24] Okitsu, K., Ashokkumar, M., Grieser, F., 2005b. Sonochemical synthesis of gold nanoparticles in water: effects of ultrasound frequency. *J. Phys.Chem. B* 109, 20673–20675.
- [25] Hua, I., Hoffmann, M.R., 1996. Kinetics and mechanism of the sonolytic degradation of CCl₄: Intermediates and byproducts. *Environ. Sci.Technol.* 30, 864–871.
- [26] K.Okitsu, K. Kawasaki, B. Nanzai, N.Takenaka, H. Bandow, Effect of carbon tetrachloride on sonochemical decomposition of methyl orange in water, *chemosphere* 71 (2008) 36–42.
- [27] Sunartio, D., Ashokkumar, M., Grieser, F., 2007. Study of the coalescence of acoustic bubbles as a function of frequency, power, and watersoluble additives. *J. Am. Chem. Soc.* 129, 6031–6036.