



An integrated approach using ozone nanobubble and cyclodextrin inclusion complexation to enhance the removal of micropollutants

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ABSTRACT

Ozone (O₃) has been widely used for the elimination of recalcitrant micropollutants in aqueous environments, due to its strong oxidation ability. However, the utilization efficiency of O₃ is constrained by its low solubility and short half-life during the treatment process. Herein, an integrated approach, using nanobubble technology and micro-environmental chemistry within cyclodextrin inclusion cavities, was studied in order to enhance the reactivity of ozonisation. Compared with traditional macrobubble aeration with O₃ in water, nanobubble aeration achieved 1.7 times higher solubility of O₃, and increased the mass transfer coefficient 4.7 times. Moreover, the addition of hydroxypropyl- β -cyclodextrin (HP β CD) further increased the stability of O₃ through formation of an inclusion complex in its molecule-specific cavity. At a HP β CD:O₃ molar ratio of 10:1, the lifespan of O₃ reached 18 times longer than in a HP β CD-free O₃ solution. Such approach accelerated the removal efficiency of the model micropollutant, 4-chlorophenol by 6.9 times, compared with conventional macrobubble ozonation. Examination of the HP β CD inclusion complex by UV-visible spectroscopy and Nuclear Magnetic Resonance analyses revealed that both O₃ and 4-chlorophenol entered the HP β CD cavity, and Benesi-Hildebrand plots indicated a 1:1 stoichiometry of the host and guest compounds. Additionally, molecular docking simulations were conducted in order to confirm the formation of a ternary complex of HP β CD:4-chlorophenol:O₃ and to determine the optimal inclusion mode. With these results, our study highlights the viability of the proposed integrated approach to enhance the ozonation of organic micropollutants.

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1. Introduction

Organic micropollutants, such as pesticides (Lv et al., 2016), pharmaceutical and personal care products (Zhang et al., 2018), have been extensively detected in various aquatic systems, and pose a serious risk to the environment and to human health. A majority of such emerging contaminants have been reported to only achieve limited treatment efficiencies by conventional wastewater treatment plants, and thus development of alternative approaches toward more effective removal technologies is urgently required (Falás et al., 2016; Lyu et al., 2018). Due to a superior oxidation potential (2.07 V), the widely used ozone (O₃) treatment technology exhibits high capability for the oxidation of pharmaceuticals in drinking water (Prasse et al., 2012), remediation of antibiotics in wastewaters (Alexander et al., 2016), and removal of recalcitrant organic pollutants in groundwater (Hu and Xia, 2018). Molecular

O₃ not only oxidises such pollutants directly, but also acts as a precursor to generate the hydroxyl radical (\bullet OH) that is even more reactive as a nonselective oxidant (Kim et al., 2020). Nevertheless, efficient ozonisation is still restricted by low water solubility (e.g. < 10 mg L⁻¹ in typical groundwater) and short half-life (typically < 1 h) (Khan and Carroll, 2020), and remains a significant technological challenge.

Many efforts have been made to enhance the ozonation process, including the addition of peroxides and thiosulfate (Yang et al., 2020), coupling ozonation with photocatalytic/electrolytic processes (Mehrijouei et al., 2015), and catalysis by metal ions or metal oxides (Nawrocki and Kasprzyk-Hordern et al., 2010). These approaches mainly focus on promoting the generation of \bullet OH from O₃, thus resulting in better oxidation of refractory organic contaminants (Yang et al., 2020). However, such optimisations still do not increase the solubilisation or prolong the reactivity of aqueous O₃.

Nanobubbles are defined as bubbles with a diameter of less than 1000 nm and possess special characteristics compared with normal macrobubbles, such as low buoyancy and long lifetimes

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(Zimmerman et al., 2011; Wang et al., 2020). In addition, the smaller bubbles have a greater surface area per unit volume and could therefore increase the gas transfer rate into the surrounding water, significantly improving O_3 dissolution (Parmar and Majumder, 2015). Previous studies have demonstrated that the mixture of micro- and nanobubbles could increase the mass transfer coefficient ($K_L a$) of O_3 by 2 times higher than that of macrobubbles (Gao et al., 2019). Moreover, it has been reported that nanobubbles can exist in water for days due to their low buoyancy (Ghaani et al., 2020). These unique characteristics of O_3 nanobubbles have been used to enhance the *in-situ* remediation of trichloroethylene-contaminated groundwater (Hu and Xia, 2018). Although the improvement of O_3 dissolubility and mass transfer rate through nanobubble technology could facilitate the ozonation process, the short half-life caused by the undesirable consumption of the oxidant, i.e. O_3 and $\bullet OH$, by non-target compounds and radical scavengers (Gardoni et al., 2012; Yuan et al., 2020) still limit the utilisation efficiency of O_3 .

Currently, some chemical stabilisers have been developed to address this issue. amongst them, addition of gentle organic acids such as acetic, propionic and short-chain fatty acids have been proven to increase the half-life of O_3 during ozone-based treatments (Alcantara-Garduno et al., 2008; Britton et al., 2020). Fan et al. (2020) reported that complete attenuation of O_3 could take 2.5 h in 5% acetic acid solution (pH = 2.56), which is 100 min longer than in pure water. Nevertheless, these acidic effluents would need further treatment before discharge, which would incur considerable hidden costs for the application. Another promising method was through use of cyclodextrins (CDs), which contain doughnut-shaped molecular structures with a hydrophilic outer shell and a hydrophobic inner cavity (Cai et al., 2015; Dettmer et al., 2017; Khan et al., 2018). This low polarity cavity can encapsulate dissolved size-matched guest compounds via coordination through various weak interactions (e.g. hydrophobic interactions, hydrogen bonds, and steric effects) and features molecular recognition capabilities (Fernández et al., 2019; Liu et al., 2020). Such inclusion complexes could increase the stabilisation of the enclosed molecules and prolong their lifespan, which would have the effect of also increasing the apparent solubility of low polarity organic compounds and thus their availability for removal (viz. sorption or degradation) (Cheirsilp and Rakmai, 2016; Zhou et al., 2018, 2020). According to this concept, Dettmer et al. (2017) initially investigated the hydroxypropyl- β -cyclodextrin (HP β CD): O_3 clathrate complex as an ozone stabilizer. The addition of HP β CD has been further proven to significantly enhance the ozonation of 1,4-Dioxane, Trichloroethylene and 1,1,1-Trichloroethane (Khan et al., 2019). Nevertheless, the molecular structures of the complexes and the dynamics of their formation need further study in order to reveal the underpinning mechanisms.

The purpose of this study was to investigate the combined approach of using O_3 nanobubbles and HP β CD to overcome the dual problems hitherto inherent in the ozonation process for remediation of organic pollutants. HP β CD, as a cost-effective and eco-friendly model cyclodextrin (Gloud and Scott, 2005), was selected to evaluate the proposed approach for micropollutants remediation. The main hypothesis is that the O_3 nanobubbles could increase the solubility and transfer efficiency of O_3 , then the dissolved ozone could enter into the cyclodextrin cavity which would inhibit their otherwise rapid decay. Therefore, in this study, the improvement of O_3 solubility and mass transfer rate, through application of nanobubble technology, was first examined. Furthermore, different HP β CD: O_3 molar ratios were utilised in order to investigate the lifespan of the complexed O_3 , and the dynamics of decay of the generated reactive oxygen species (ROs), i. e. $\bullet OH$ and H_2O_2 . The removal performance and degradation kinetics of

4-chlorophenol, a model micropollutant, were monitored in order to further evaluate the proposed integrated ozonation technique. In order to understand the mechanisms, UV-visible spectroscopy (UV-vis) and nuclear magnetic resonance (NMR) analysis were used to characterise the HP β CD inclusion complex and molecular docking simulations were conducted to reveal probable modes of inclusion formation.

2. Materials and methods

2.1. Chemicals

Hydroxypropyl- β -cyclodextrin (HP β CD, $C_{63}H_{112}O_{42}$, 98%) was purchased from Yuanye Bio-Technology Co., Ltd (Shanghai, China). A typical organic micropollutant, 4-chlorophenol, was selected as the model contaminant in this study, which exhibits high toxicity and persistence characteristics in an aquatic environment. deionized (DI) water (>18.2 M Ω ; Milli-Q Academic, Millipore, USA) was used to prepare all solutions.

2.2. Ozone nanobubble and macrobubble generation

Oxygen (99.5%, Juyang Co., Ltd, China) was used as the gas source for O_3 generation (CH-ZTW7G, Chuanghuan, China). The flow rate and concentration of the O_3 gas into a pressurized dissolution type nanobubble generator (Model XZCP-K-0.75, Xiazhichun, China) were approximately 0.5 L min^{-1} and 38 mg L^{-1} , respectively. The macrobubble aeration was prepared using a microporous plate diffuser (SB718, Songbao, China). The concentration and inflow rate of the O_3 for this diffuser were same as for nanobubble generation. The size and distribution of nanobubbles after generation were analysed with a Coulter Multisizer 4e (Beckman Coulter, Brea, USA). The size range of macrobubbles was estimated by analysing a digital image acquired under strong light (3500 lm, Magnaten D6, China), using ImageJ software (v 1.5, Schneider et al., 2012; Desai et al., 2019). The aqueous O_3 concentration was monitored using the indigo dye method (Rakness et al., 2010; Wang et al., 2019). Briefly, 9 mL sample was placed into a glass colorimetric tube and 1 mL of indigo solution (1.25 mM) was added. The absorption measurements for the indigo method were performed at 600 nm on a spectrophotometer (GENESYS 10S UV-VIS, Thermo Fisher Scientific, USA). The volumetric mass transfer coefficient ($K_L a$) of O_3 to water was determined during O_3 aeration according to the following equation (Fan et al., 2020): $K_L a = \ln(C_t/(C_s - C_t))/t$, where C_t (mg L^{-1}) is the O_3 concentration at the aeration time t (min) and C_s (mg L^{-1}) is the saturated dissolved O_3 concentration.

2.3. Ozone decay experiment

The decay kinetics of O_3 after the addition of HP β CD in O_3 nanobubble and macrobubble solutions were examined. Initially, water aliquots (50 mL) in amber glass bottles (100 mL volume) were aerated by O_3 nanobubble and macrobubble streams until O_3 concentrations reached 9 mg L^{-1} as mother liquor. In order to assess the impact of HP β CD on the O_3 half-life, the amount of the dissolved O_3 was then employed to calculate the addition of HP β CD, required to achieve molar ratios of HP β CD: O_3 of 0:1, 1:1, 3:1, 5:1 and 10:1. These bottles were then sampled by gastight syringe at various time intervals up to 72 h, and both concentrations of aqueous O_3 and generated ROs, including $\bullet OH$ and H_2O_2 , were immediately analysed. Hydroxyl $\bullet OH$ radicals were determined using a formaldehyde capturing method, while H_2O_2 was measured using the N, N-diethyl p-phenylenediamine/horseradish peroxidase method (Fan et al., 2020). The details for determining these free radicals were shown in the Supplementary Information

(Text S1). All experiments were conducted in triplicate and terminated when the remaining O₃ concentration reached zero. The dynamics of O₃ concentrations in different groups were simulated by the first-order kinetics mode, and the decay rates (*k*) of O₃ were calculated from the slopes of the ln(*C_t/C₀*)-*t* regressive lines, where *C_t* denoted the O₃ concentration at time *t*, and *C₀* was the starting O₃ concentration (6 mg L⁻¹). The half-life of O₃ was defined as the duration over which the initial O₃ concentration decreased by half. The lifespan of O₃ was defined as the time elapsed from the start of measurement until it could not be detected in the solution.

2.4. Integrated approach for 4-chlorophenol removal

The removal efficiencies of 4-chlorophenol during the ozonation process, under the integrated approach of O₃ nanobubble aeration and HPβCD addition, were evaluated. Water contaminated with 4-chlorophenol was prepared with an initial concentration of 30 mg L⁻¹. In the treatment groups, aeration with O₃ macrobubbles or nanobubbles was applied to achieve initial O₃ concentrations of 6 mg L⁻¹. Meanwhile, HPβCD was added into the solution to achieve initial molar ratios of HPβCD: O₃ from 0:1 to 10:1 (Section 2.3). A solution containing 4-chlorophenol at the same concentration, but without O₃ and HPβCD, were prepared as a control. The sampling procedure was the same as that described in Section 2.3. The concentrations of 4-chlorophenol during treatment were determined by high-performance liquid chromatography (Agilent 1200 series, Agilent Technologies, Santa Clara, USA) with a C18 column (Text S1).

2.5. Characterisation of inclusion interactions and measurement of binding constants

Separate host (HPβCD) and guest (O₃ or 4-chlorophenol) stock solutions were mixed to create various molar ratios with or without nanobubbles, as described previously. The physiochemical properties of the guest molecule caged within the host cavity were found to be very different from those of the free guest compounds (Karoyo and Wilson et al., 2019; Banjare et al., 2020). The host-guest complex formed from HPβCD:O₃ was monitored using UV-Visible spectrophotometry, and detection of the HPβCD:4-chlorophenol complex was conducted by a fluorescence titration method (Lin et al., 2020) and by NMR. The procedures for ¹H NMR and 2D ROESY NMR analyses are described in Text S2. The binding constants of HPβCD-O₃ and HPβCD-4-chlorophenol inclusion complexes, indicative of inclusion potential, could be explained by the Benesi-Hildebrand Eq. (1) (Cai et al., 2015; Khan et al., 2019).

$$\frac{1}{\Delta F} = \frac{1}{\alpha K C_g [C_0]^n} + \frac{1}{\alpha C_g} \quad (1)$$

where ΔF is the change of absorbance of O₃ or fluorescence intensity of 4-chlorophenol in the presence or absence of HPβCD at different molar ratios of HPβCD: O₃; α is a constant related to the quantum yield of the complex and instrument itself; C_g is the concentration (mM) of the guest substrate (O₃ or 4-chlorophenol); C_0 is the concentration (mM) of HPβCD; n is the ratio of HPβCD to O₃ or 4-chlorophenol in the complex. K is the binding constant of the complex, corresponding to a ratio of the intercept to the slope.

2.6. Molecular docking simulation

The 3D structure of HPβCD was retrieved using PyMOL (The PyMOL molecular graphics system, Version 2.0 Schrödinger, LLC) from the native β-CD (PDB ID: 3CGT) in which the hydroxyl groups at the rim of the glucose unit were substituted with hydroxypropyl groups. Both the 3D structure of O₃ and 4-chlorophenol were structurally optimized with molecular mechanics method and

plotted with Chem3D (v15.0, PerkinElmer Infomatics, Waltham, USA) (Zhang et al., 2017). To understand the interaction of HPβCD with a complexing ligand, molecular docking was executed using Autodock Tools (Version 4.2; Scripps Research Institute, San Diego, USA) (Morris et al., 2009). The binding energies and molecular structures of the complexes were determined when O₃ and/or 4-chlorophenol were introduced into the HPβCD cavity. AutoDock's Lamarckian Genetic Algorithm (LGA) was applied to identify possible binding modes of O₃ and/or 4-chlorophenol with HPβCD through the entire process (Rasdi et al., 2019). A three-dimensional grid box of 52, 48, and 50 Å size in the x, y, and z directions was constructed using Autogrid (Scripps Research Institute, San Diego, USA) with a spacing of 0.375 Å centred on HPβCD. The grid box was appropriately designed to sufficiently enclose not only the HPβCD hollow region but also its exterior part. The interaction energy (ΔE) was then calculated by considering different molecular forces, including Van der Waals, electrostatics, hydrogen bonding, desolvation, and torsional (Rasdi et al., 2019). Different conformations with different binding energies were generated, and the most stable conformation with the lowest ΔE energy value was identified as the best binding mode in each docking simulation. The 3D model of the docking results was again visualized using PyMOL. The molecular structures of O₃, 4-chlorophenol, βCD, and HPβCD are illustrated in Fig. S1.

3. Results and discussion

3.1. Enhanced solubilisation of O₃ by nanobubbles

The concentration of bubbles in the O₃ nanobubble aeration group achieved 2.16 × 10⁵ particles mL⁻¹. Over 93.4% of the bubbles could be categorised as nanobubbles (<1000 nm) with a median diameter of 580 nm (Fig. 1a), whereas in the macrobubble aeration system, the average diameter of the bubbles was 1.82 mm, approximately 3.5 orders of magnitude higher (Fig. 1c). The O₃ concentration increased quickly after aeration began and then approached a quasi-steady state in both groups after 20 min (Fig. 1b). Bubble size distribution affects the O₃ content in water, because bubbles of smaller size have a proportionally greater surface area than large bubbles and can give an enhanced rate of gas transfer (Parmar and Majumder, 2015). Moreover, nanobubbles, due to the low buoyance, have longer residence time in the liquid and display certain stability (Ghaani et al., 2020), which would extend the gas transfer process. Thus, the O₃ nanobubble aeration resulted in the oversaturation of O₃ with the dissolved O₃ concentration of 13.4 mg L⁻¹ and mass transfer coefficient ($K_L a$) of 0.179 min⁻¹, which were 1.7 times and 4.7 times higher than those (7.9 mg L⁻¹ and 0.038 min⁻¹) measured from the macrobubble aeration group. Due to the smaller size of the nanobubbles, the increase of $K_L a$ was even 2 times higher compared with the value from the group utilising the mixture of micro- and nanobubble aeration (Gao et al., 2019).

Notably, a previous study has measured heterogeneous pressure inside nanobubbles by atomic force microscopy. This was further modelled by a molecular dynamics simulation and confirmed the high-gas-density state in nanobubbles (Zhang et al., 2006). The gas inside nanobubbles may exist as an aggregation, rather than an ideal gas phase, and the diffusion of the O₃ inside nanobubbles is likely to be slow and take place over a long period. Overall, the results demonstrated that O₃ nanobubble aeration could significantly increase solubilisation, and gas transfer efficiency, of O₃ and may sustainably supply O₃ to the surrounding water, which may enhance the ozonation of pollutants.

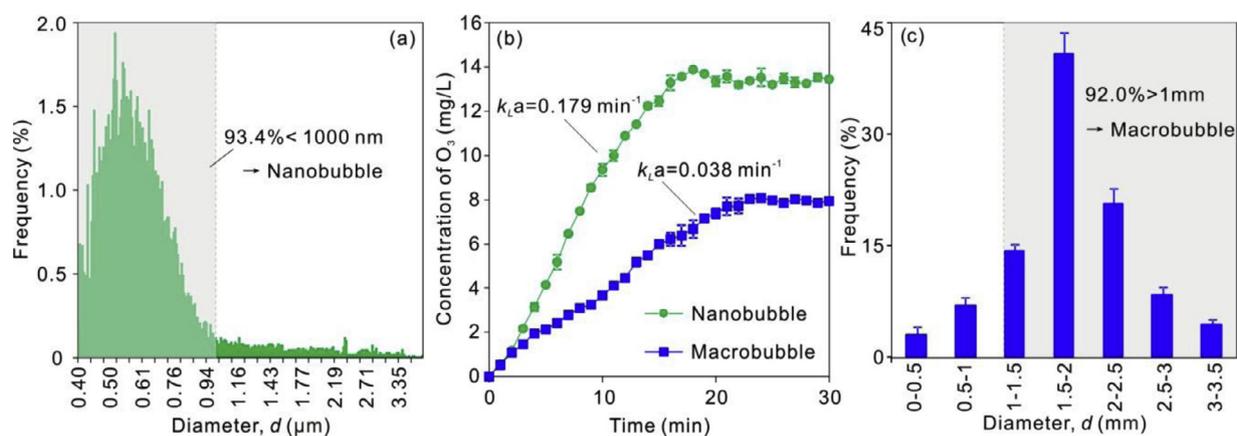


Fig. 1. (a) Size distribution of nanobubbles; (b) The time course of O₃ concentration during nanobubble and macrobubble aeration scenarios; (c) Size distribution of macrobubbles.

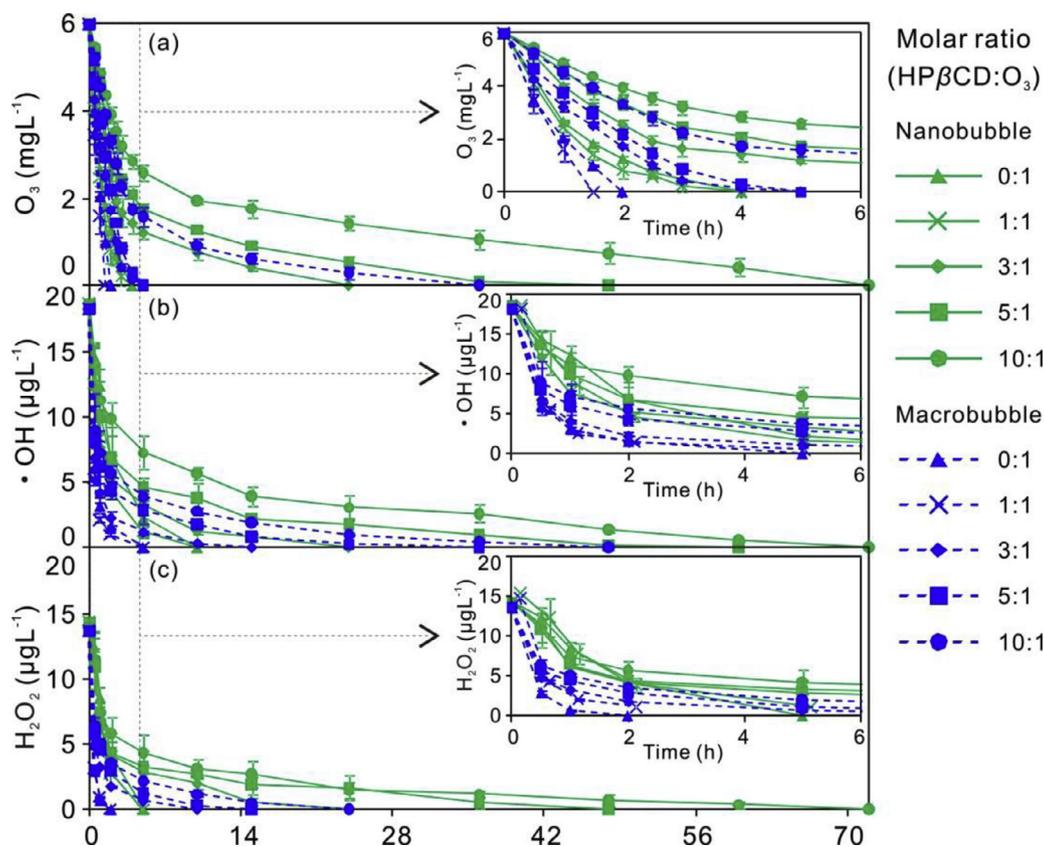


Fig. 2. Ozone decay (a), and produced reactive oxygen species, •OH (b) and H₂O₂ (c), after nanobubble and macrobubble aeration under different HPβCD:O₃ molar ratios.

3.2. Improved stabilisation of O₃ by HPβcd inclusion complex

HPβCD is an environmentally-benign, glucose-based, non-toxic molecule containing hydroxypropyl groups attached on the outside of the macrocyclic cone (Fig. S1) (Bezamat et al., 2020). In order to conduct a comparative study to evaluate the effect of HPβCD on O₃ stabilisation, the decay of dissolved O₃ (Fig. 2a), from an initial O₃ concentration of 6 mg L⁻¹, and reactive oxygen species produced thereof, i.e. •OH (Fig. 2b) and H₂O₂ (Fig. 2c), were monitored in both nanobubble and macrobubble aeration groups.

In HPβCD-free water (HPβCD:O₃ molar ratio of 0:1), aerated by macrobubbles, the lifespan of O₃ was approximately 1.75 h with a decay rate (*k*) of 1.15 h⁻¹ (Fig. 2a and Table 1). As the hydroxypropyl group of HPβCD could be oxidised, the ring in gly-

Table 1

The lifespan and decay rates of O₃ in nanobubble and macrobubble aeration groups under different HPβCD:O₃ molar ratios.

HPβCD:O ₃ molar ratio	O ₃ lifespan (h)		O ₃ decay rates (h ⁻¹)	
	macrobubble	nanobubble	macrobubble	nanobubble
0:1	1.75	3.50	1.15	0.83
1:1	1.25	3.50	1.27	0.95
3:1	4.50	19.50	0.66	0.43
5:1	4.50	42.00	0.57	0.28
10:1	30.00	66.00	0.29	0.19

cosides remains stable in the presence of oxidants, including O₃ (Manhas et al., 2007; Dettmer et al., 2017). Addition of small

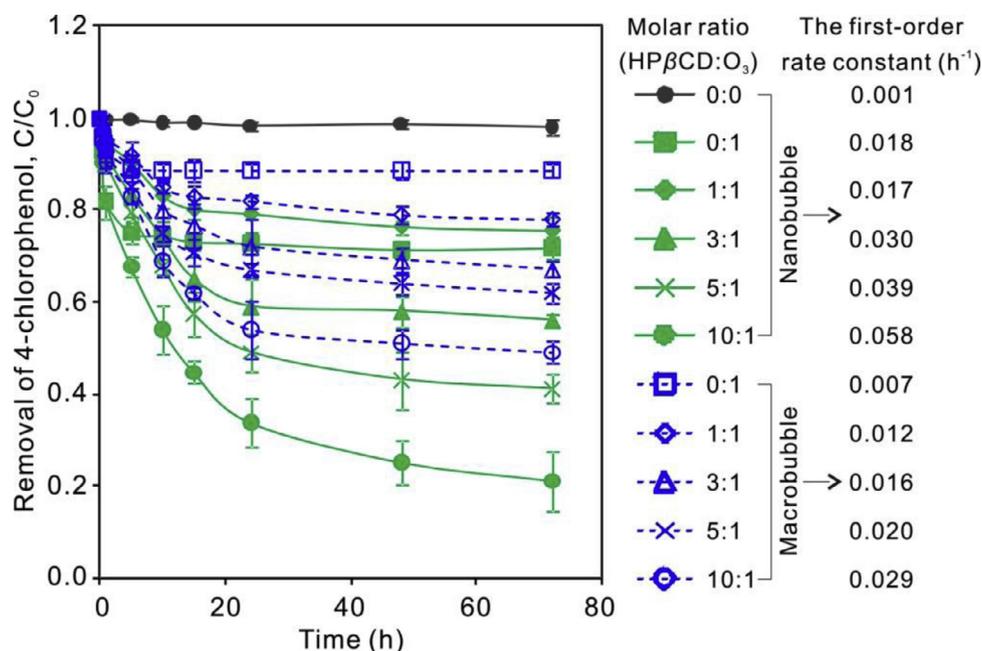


Fig. 3. Removal of 4-chlorophenol by nanobubble and macrobubble ozonation processes at different HPβCD: O₃ molar ratios (0:1 to 10:1).

amounts of HPβCD, e.g. HPβCD:O₃ molar ratio below 1:1, could not slow down the decay of O₃ (Fig. S2). In the current study, along with the increase of HPβCD:O₃ molar ratio from 1:1 to 10:1 in the macrobubble aerated group, the O₃ decay rates decreased from 1.27 to 0.29 h⁻¹ with a prolonged lifespan of up to 30 h (Fig. 2a and Table 1). This observation was mainly attributed to the molecular dimensions of the β-CD cavity which could readily form inclusion complexes through host-guest interactions (Szente et al., 2018). Khan et al. (2019) reported that significant amounts of O₃ and/or contaminants could enter the clathrate cavity and thus enhance their interaction through proximity effects. More importantly, the O₃ decay rates (0.19–0.95 h⁻¹) in the O₃ nanobubble aeration group were 0.49–0.75 times lower, and O₃ lifespans (3.5–66 h) were 2.00–9.33 times higher, than those determined from the macrobubble aeration group, at the same HPβCD:O₃ molar ratio (Fig. 2a and Table 1). The aforementioned higher mass transfer efficiency and longevity of nanoscale O₃ bubbles may have further contributed to the stabilization of O₃, displaying a synergistic effect with HPβCD.

In addition, the ROSs produced upon the decomposition of O₃ play a crucial role for removal of pollutants through ozonation (Kim et al., 2020). Thus, nanobubble-HPβCD-mediated O₃ decay kinetics in different scenarios were further confirmed by the detection of •OH and H₂O₂ (Fig. 2b and 2c). The •OH and H₂O₂ could be detected in macrobubble aeration groups in the initial 2–30 h (Fig. 2 and Table 1), while they remained from 0 to 32 and 0.37–0.66 μg L⁻¹ after 36 h in the nanobubble aeration groups, under various HPβCD:O₃ molar ratios. The results confirmed that the addition of HPβCD could extend the lifetime of O₃ and promote the production of ROSs. Moreover, these functions were strengthened under the application of O₃ nanobubbles.

3.3. The integrated approach for 4-chlorophenol removal

The decomposition of 4-chlorophenol was investigated and comparisons made between the nanobubble and macrobubble ozonation processes at different HPβCD:O₃ molar ratios (Fig. 3). In the blank control group (without the addition of HPβCD and ozone), the concentration of 4-chlorophenol was stable along the whole experimental period (Fig. 3). In the groups without the addi-

tion of HPβCD, the removal efficiency of 4-chlorophenol were significantly higher in nanobubble aeration group (28.33%) compare with that (11.51%) in the macrobubble aeration group. Removal of 4-chlorophenol was enhanced with increasing HPβCD addition, until at a HPβCD:O₃ molar ratio of 10:1, removal of up to 79.0% and 51.0% in the nanobubble and macrobubble aeration groups, respectively, were observed. At each HPβCD:O₃ molar ratio, the application of O₃ nanobubbles always resulted in 12.1–146.15% higher removal efficiencies of 4-chlorophenol compared with treatment with macrobubbles. The removal efficiency at HPβCD:O₃ molar ratio of 10:1 by nanobubble ozonation was up to 6.9 times higher when compared with the 'normal' O₃ macrobubble treatment without addition of HPβCD. Note that the continuing improved removal capabilities of 4-chlorophenol along with the increased HPβCD:O₃ molar ratio from 1 to 10, may due to current amount of HPβCD has not reached saturation level for incusing complex formation. A lot of experiments should be further conducted to investigate the threshold of the HPβCD:O₃ molar ratio towards maximising 4-chlorophenol removal when this integrated approach is used in practical wastewater treatment.

Benitez et al. (2000) reported that the ozonation process of 4-chlorophenol could be described by a first-order kinetics model, which was also applied to the current study. First-order rate constants, estimated from the removal dynamics of 4-chlorophenol (Fig. 3) in the nanobubble emulsion, were 0.017, 0.030, 0.039, and 0.058 h⁻¹ for HPβCD:O₃ molar ratios of 1:1, 3:1, 5:1, and 10:1, respectively. In contrast, the constants were 0.012, 0.016, 0.020, and 0.029 h⁻¹ from the corresponding macrobubble ozonation process. Both O₃ and ROSs could contribute to the oxidation of organic micropollutants (Van Aken et al. 2019), thus, the prolonged survival of O₃ and ROSs (Fig. S3) led to enhanced removal efficiency of 4-chlorophenol from the integrated approach of nanobubbles and addition of HPβCD (Fig. 3).

3.4. Measurement of inclusion complex binding

Binding constants were evaluated by analysing the variation of the absorbance of O₃ and the fluorescence emission intensity of 4-chlorophenol with host (HPβCD) concentration. O₃ has a characteristic absorption peak at 260 nm, which is clearly different from

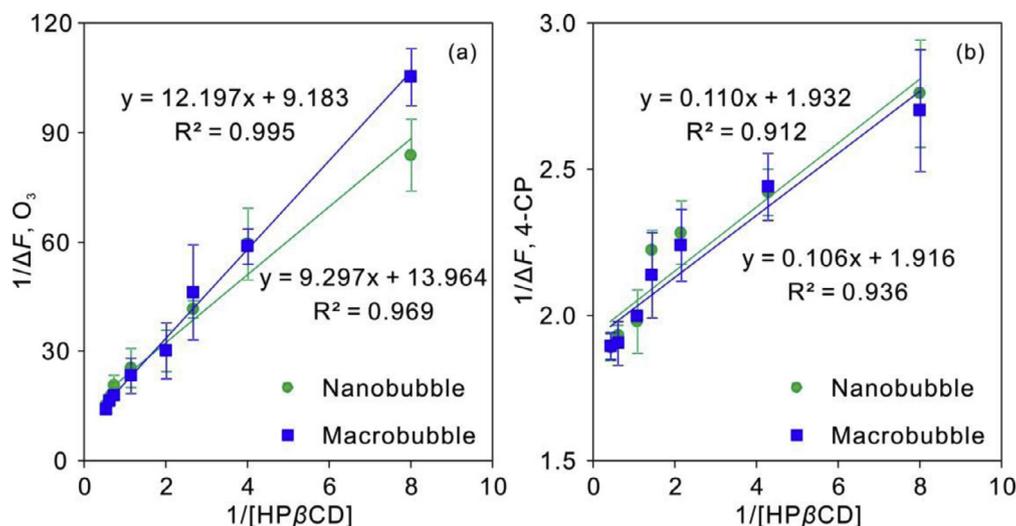


Fig. 4. Benesi-Hildebrand plots for O_3 and 4-CP in macrobubble and nanobubble aerated solutions at different HP β CD: O_3 molar ratios (0.5:1 to 15:1). The lines represent regression results used for binding equilibrium analyses.

the adsorption spectrum of HP β CD (Fig. S4). Moreover, the excitation wavelength maximum of 4-chlorophenol was noted around 330 nm, where the fluorescent response of HP β CD was very weak (Fig. S5). Notably, the absorbance of O_3 decreased with increasing concentration of HP β CD, while the fluorescence intensity of 4-chlorophenol increased. These two aspects are consistent with previous studies on the formation of inclusion compounds with HP β CD (Khan et al., 2019; Faisal et al., 2020). The response of absorbance of O_3 was attributed to the high electron density in the cavity of HP β CD, which could cause alteration in the valence electron characteristics in the O_3 molecule, an increase in the difference in electron transition energy and a decline in the electron transition probability (Shi and Zhou, 2011). The increase in rigid planarity, caused by the insertion of 4-chlorophenol into the hydrophobic cavity of HP β CD (Lin et al., 2020) may be responsible for the increase in intensity of fluorescence of 4-chlorophenol.

The Benesi-Hildebrand plots indicated that $1/[HP\beta CD]$ values displayed a positive linear relationship with the $1/\Delta F$ values of both O_3 and 4-chlorophenol (Fig. 4), suggesting that the stoichiometry of host and guest complexes was 1:1 in this study ($n = 1$). The average inclusion constant K for O_3 and 4-chlorophenol with macrobubble treatment were 0.75 mM^{-1} and 17.56 mM^{-1} , respectively, whereas they were determined to be 1.50 mM^{-1} and 18.06 mM^{-1} with nanobubbles, respectively. Although the presence of nanobubbles showed a negligible impact on the K of the HP β CD-4-chlorophenol complex, however, it significantly increased the K of the HP β CD- O_3 complex. It may be observed that the regression line of data from the nanobubble aerated group yields larger intercept and smaller slope values than that of data measured from the macrobubble aeration group (Fig. 4a, Fig. S6). It has been reported that the host-guest interaction can be judged by calculation of the Gibbs energy of binding ΔG , $\Delta G = -RT \ln K$ (Srinivasana et al., 2012), where, $R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$ (the gas constant per molecule), and K is the Kelvin temperature (294.3 K). The calculated ΔG herein were -16.20 and $17.89 \text{ kJ mol}^{-1}$ for the HP β CD- O_3 -macrobubble and HP β CD- O_3 -nanobubble systems, while they were -23.91 and $-23.98 \text{ kJ mol}^{-1}$ for HP β CD-macrobubble-4-chlorophenol and HP β CD-nanobubble-4-chlorophenol complexes, respectively. Since the values of ΔG were all negative, the inclusion process proceeded spontaneously at the test temperature and the complex formation was demonstrated as an exergonic process (Khan et al., 2019).

3.5. Characterisation of inclusion complexes

The HP β CD: O_3 inclusion complex can be effectively detected using spectrophotometry. The optimum adsorption wavelength of O_3 was 260 nm, while HP β CD recorded no absorbance at this wavelength. The absorbance of O_3 increased upon the addition of HP β CD at a specific time (Fig. 5), and the absorbance for specific HP β CD: O_3 scenarios decreased gradually over time. A slight bathochromic shift (2–3 nm) was observed with increasing concentrations of HP β CD (Fig. S7), which has been reported previously with other guest molecules and has been explained in terms of a change in the environment of the molecule as it is included within the CD cavity (Hendy and Breslin, 2011; Lin et al., 2020). Usually, O_3 would have been completely degraded after 1–3 hour in DI water (Dettmer et al., 2017), however in this study, absorption peaks were still observed even after 12 h in the presence of HP β CD (Fig. 5a and Fig. S7). These variation of absorbance intensity with time suggested that the formation of the inclusion complex is reversible. Thus HP β CD acted as “sustained-release capsules” for ozone oxidation.

The formation of an inclusion complex can affect the protons of the HP β CD and 4-chlorophenol molecules, which then results in changes in their chemical shifts (δ) in ^1H NMR spectra (Fig. S8) (Hendy and Breslin, 2011). Once a 4-chlorophenol molecule is placed inside the HP β CD cavity, the internal protons of HP β CD are involved in upfield shift changes of $\Delta\delta$ (for H3, $\Delta\delta = 0.021$; for H5, $\Delta\delta = 0.015$). For 4-chlorophenol, a shift of H1' (0.001), H2' (-0.008), and -OH (0.004) were synchronously observed. This internal interaction for HP β CD:4-chlorophenol was further elucidated by 2D ROESY NMR (Fig. 5b). Cross peaks in the two-dimensional plot indicate the intermolecular Nuclear Overhauser Effects (NOEs) between the 4-chlorophenol and HP β CD cavity protons. Of note, a strong cross-peak indicated interaction between proton H3 of HP β CD ($\delta = 3.764$) and the hydroxyl group of the proton from 4-chlorophenol ($\delta = 9.657$). These cross-peaks are marked by green boxes in Fig. 5b. The close proximity of these protons (distance less than 4 Å) indicated the inclusion of 4-chlorophenol into the HP β CD cavity (Adhikari et al., 2018).

3.6. Molecular docking simulation of inclusion complexes

To further elucidate the inclusion geometry of O_3 and 4-chlorophenol with HP β CD, molecular docking simulations were

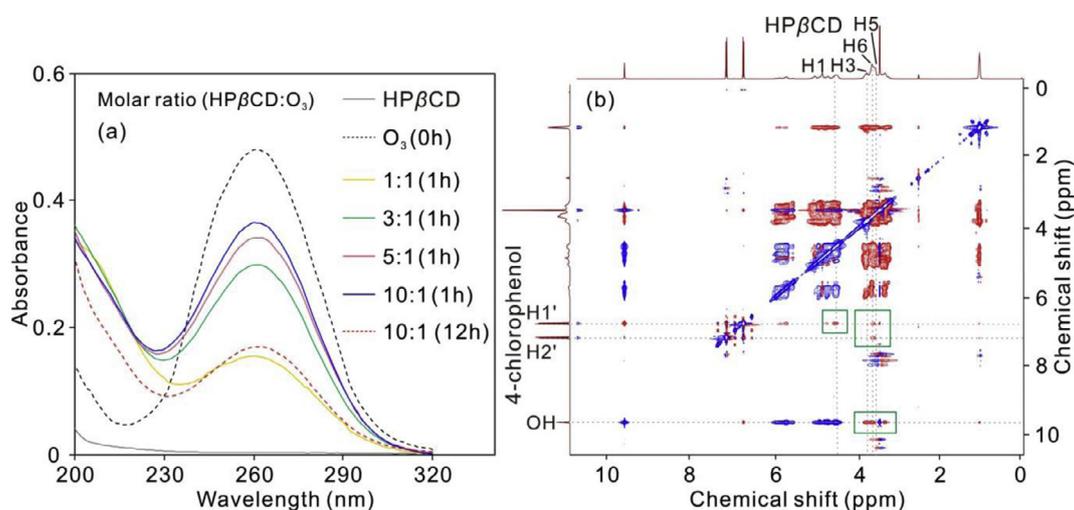


Fig. 5. (a) UV spectra of O_3 in the absence and presence of HP β CD at varying molar ratios of HP β CD: O_3 . (b) 2D ROSEY spectra of HP β CD complexes with 4-CP.

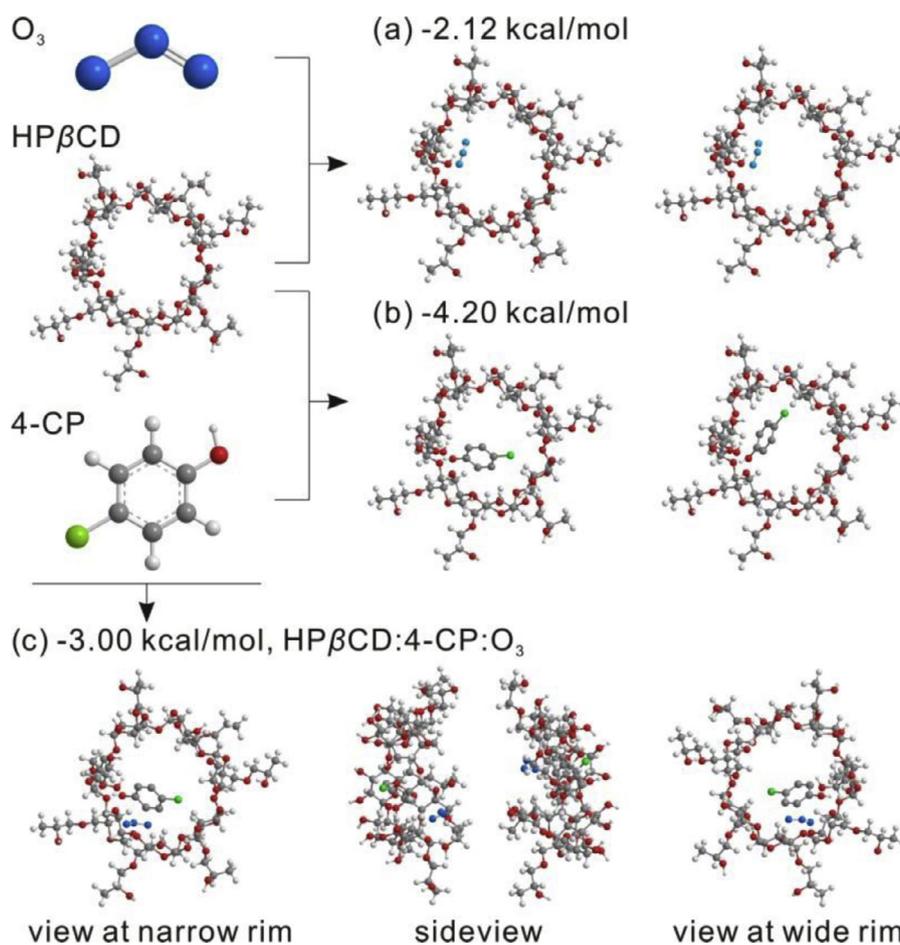


Fig. 6. Complexed structures of HP β CD: O_3 (a), HP β CD:4-chlorophenol (b), two binding orientations with the same interaction energy were presented herein; and HP β CD:4-chlorophenol: O_3 (c) with optimal interaction energy from molecular docking. In this figure, 4-chlorophenol is denoted by 4-CP.

carried out, which can indicate how O_3 and 4-chlorophenol molecules could be arranged inside the HP β CD cavity in energetically favourable orientations (Gupta et al., 2018; Rasdi et al., 2019). Five conformations with different binding energies for each scenario were generated, and their docking configurations and interaction energies are shown in Tables S1– S3. The high absolute value of the binding energy means high affinity between host and guest, and thus a more stable inclusion complex (Cai et al., 2015;

Khan et al., 2019). Fig. 6 shows the most stable structure based on the docking simulations. The lowest binding energy was $-2.12 \text{ kcal mol}^{-1}$ for the stable docking conformation of HP β CD: O_3 . HP β CD cavity is non-polar and hydrophobic, while O_3 is hydrophobic with very low polarity. This triggers a weak attractive force to trap O_3 inside the HP β CD cavity.

For the complex of HP β CD:4-chlorophenol, two different binding orientations with the same lowest binding energy -4.20 kcal

mol⁻¹ were calculated. The docking results suggested that 4-chlorophenol can insert, slantwise, into the cavity of HPβCD (Fig. 6b and c). The -OH group of 4-chlorophenol is always contained inside the cavity in either inclusion mode, which substantiated the results of 2D NMR analysis (Fig. 5b). We speculated that the -OH group in 4-chlorophenol is able to undertake hydrogen bonding with -OH groups inside the HPβCD cavity. Due to the free rotation of the hydroxypropyl on the narrower rim which would lead to a steric effect, the most likely mode of complexation would be an insertion into the cavity from the wider rim (Ge et al., 2011). Note that the -Cl group in 4-chlorophenol locates near the narrower rim in both docking configurations (Fig. 6b and c), 4-chlorophenol may enter the cavity with the relatively hydrophobic group -Cl leading. This is verified by the upfield shifts in the ¹H NMR signals for H3, compared to H5 (Fig. 5b). The docking results illustrated in Fig. 6d indicated the formation of ternary structures where 4-chlorophenol and O₃ form inclusion complexes within the HPβCD cavity. The optimal binding energy was -3.00 kcal/mol for HPβCD:4-chlorophenol:O₃ complex. Therefore, both 4-chlorophenol and O₃ are thermodynamically favoured to partition into HPβCD, which would increase their relative concentrations and place them closer in order to facilitate reaction with each other. These results confirm that increased reactivity within the cavity leads to the observed enhanced oxidation performance.

4. Conclusions

This study developed a promising approach by coupling nanobubble technology and the addition of HPβCD in order to enhance the ozonation of an organic micropollutant in artificial contaminated water. Nanobubbles were found to promote the solubilisation and mass transfer of O₃, and also benefitted from the formation of inclusion complexes in the cavities of HPβCD, compared with conventional macrobubbles. The presence of HPβCD contributed to the stabilisation of O₃ by inclusion complexation, thereby extending the lifespan of O₃ from about one hour to dozens of hours. By addressing the two common drawbacks of ozonation, solubilisation and bubble longevity, the maximum removal efficiency of the target micropollutant, 4-chlorophenol, was 6.9 times higher, when compared with the 'normal' O₃ macrobubble treatment. Investigation into possible mechanistic processes revealed that significant amounts of O₃ and/or 4-chlorophenol could enter the HPβCD cavity through various means. Molecular modelling confirmed the formation of ternary complexes of HPβCD:4-chlorophenol:O₃ and visual configurations of possible inclusion modes were generated. Overall, nanobubbles worked as an "O₃ bank" to supply O₃ and that HPβCD facilitated the entrapment of both the contaminant target and O₃ in close proximity. This intimate co-location of reactants and enhancement of reactivity within the HPβCD cavity resulted in increased 4-chlorophenol oxidation.

Declaration of Competing Interest

None

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2021.117039.

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