

Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jes

JES
 JOURNAL OF
 ENVIRONMENTAL
 SCIENCES
www.jesc.ac.cn

Impact of pre-oxidation on the formation of byproducts in algae-laden water disinfection: Insights from fluorescent and molecular weight

Da Sheng, Lingjun Bu*, Shumin Zhu, Yangtao Wu, Jue Wang, Nan Li, Shiqing Zhou*

Key Laboratory of Building Safety and Energy Efficiency, Ministry of Education, Department of Water Engineering and Science, College of Civil Engineering, Hunan University, Changsha 410082, China

ARTICLE INFO

Article history:

Received 11 November 2021

Revised 2 December 2021

Accepted 26 December 2021

Available online 4 January 2022

Keywords:

Algal organic matters

Pre-oxidation

Disinfection by-products

ABSTRACT

Pre-oxidation has been reported to be an effective way to remove algal cells in water, but the released algal organic matter (AOM) could be oxidized and lead to the increment in disinfection by-product (DBP) formation. The relationship between pre-oxidation and AOM-derived DBP formation needs to be approached more precisely. This study compared the impact of four pre-oxidants, ozone (O₃), chlorine dioxide (ClO₂), potassium permanganate (KMnO₄) and sodium hypochlorite (NaClO), on the formation of nitrogenous (N-) and carbonaceous (C-) DBPs in AOM chlorination. The characterization (fluorescent properties, molecular weight distribution and amino acids concentration) on AOM samples showed that the characterization properties variations after pre-oxidation were highly dependent on the oxidizing ability of oxidants. The disinfection experiments showed that O₃ increased DBP formation most significantly, which was consistent with the result of characterization properties variations. Then canonical correspondent analysis (CCA) and Pearson's correlation analysis were conducted based on the characterization data and DBP formation. CCA indicated that C-DBPs formation was highly dependent on fluorescent data. The formation of haloacetic acids (HAAs) had a positive correlation with aromatic protein-like component while trichloromethane (TCM) had a positive correlation with fulvic acid-like component. Pearson's correlation analysis showed that low molecular weight fractions were favorable to form N-DBPs. Therefore, characterization data could provide the advantages in the control of DBP formation, which further revealed that KMnO₄ and ClO₂ were better options for removing algal cells as well as limiting DBP formation.

© 2022 The Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. Published by Elsevier B.V.

Introduction

Algae in lakes, rivers and long-distance water distribution systems poses a serious threat to drinking water treatment util-

ities (Rickman et al., 2013, Wang et al., 2018). Commonly, pre-oxidation processes, such as ozonation, chlorination and chlorine dioxide oxidation, are widely applied for removing algae (Ma et al., 2019). However, Algal organic matters (AOM), generated by specific cyanobacteria species (e.g. *Microcystis*

* Corresponding author.

E-mail: shiqingzhouwater@163.com (S. Zhou).

aeruginosa), could provide precursors for nitrogenous disinfection by-products (N-DBPs) (e.g., haloacetonitriles (HANs)) and carbonaceous disinfection by-products (C-DBPs) (e.g., trihalomethanes (THMs)) (Wert and Rosario-Ortiz, 2013). AOM includes extracellular organic matters (EOM) and intracellular organic matters (IOM). EOM are the excreted metabolites produced by algal cells during exponential and stationary growth phases, while IOM result from cell lysis caused by the aging of algae cells and pre-oxidation in water treatment processes (Coral et al., 2013; Henderson et al., 2008b; Pivokonsky et al., 2006). AOM can be poorly removed by coagulation and filtration, which would contribute to the formation of C-DBPs and N-DBPs during chlorination with the participation of dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) in water (Fang et al., 2010; Li et al., 2014 Wert and Rosario-Ortiz, 2013).

Furthermore, the released AOM can be degraded into small molecular weight (MW) organic compounds during pre-oxidants (Jia et al., 2018; Naceradska et al., 2017; Wang et al., 2021a), which can change the DBP formation potential (DBFP) of AOM (Dong et al., 2021). Being treated in different pre-oxidation processes, the DBFP of AOM changed differently. Furthermore, different kinds of DBPs show different trends. Previous studies showed that the trichloromethane (TCM) formation during chlorination of two algae species were increased when pre-ozonation was performed (Plummer and Edzwald, 2001), while formation of haloacetic acids (HAAs), and total organic halogen for tested water samples decreased (Hua and Reckhow, 2007). Shi et al. (2019) tested TCM formation from two algae species after potassium permanganate (KMnO_4) pre-oxidation, and found that the TCM yield for two algal species decreased with the increasing dosage of KMnO_4 pre-oxidation, but increased with the increasing dosage of pre-chlorination (Shi et al., 2019). While there have been several studies implemented on the DBP formation of AOM with different pre-oxidation process, the correlation between oxidants and different kinds of DBPs formation is not clear.

To characterize the DBFP of AOM, various water quality indicators are used, including (1) the ratio of DOC to DON (Tomlinson et al., 2016; Zhou et al., 2015); (2) UV absorbance (Hong et al., 2013; Hua et al., 2019b); (3) Zeta potential (Lee et al., 2019); (4) EEM spectroscopy (Chen et al., 2020; Dong et al., 2019); (5) FTIR spectroscopy (Wan et al., 2019). These indicators showed valuable information about the possible composition of samples, and provided us more insights into the relationship between characterization properties and DBP formation (Guo et al., 2017; Liu et al., 2019). Thus, characterization on pre-oxidized samples could allow us to further understand the connection between pre-oxidation and DBP formation in subsequent chlorination, which could be beneficial for choosing suitable pre-oxidants and limiting DBP formation.

The objectives of this study were to present a comparison of the impacts of four commonly used pre-oxidants, i.e., O_3 , KMnO_4 , ClO_2 , NaClO on the formation of AOM-derived DBPs. To better understand the issue, variations on following characterizations of AOM after pre-oxidation were studied: (1) MW distributions; (2) EEM fluorescent spectroscopy; (3) amino acids concentration, and then statistical methods including Canonical correspondent analysis (CCA) and Pearson's corre-

lation analysis were used to investigate the relationship based on the characterization data.

1. Materials and methods

1.1. Chemicals and reagents

The purchased chemicals and reagents used in the study were of analytical grade. The detailed information of them were shown in Appendix A Text S1.

1.2. Experimental procedures

1.2.1. Algae cultivation and AOM extraction

Microcystis aeruginosa (FACHB-912) was purchased from the Institute of Hydrobiology, Chinese Academy of Sciences. The algae cultivation and AOM extraction methods were mentioned in our previous study (Sheng et al., 2021) and listed in Appendix A Text S2.

1.2.2. Pre-oxidation and chlorination experiments

A high concentration of gaseous ozone from bottled oxygen was used to make ozone stock solutions as mentioned in our previous study (Zhou et al., 2015). A ClO_2 stock solution was produced by reaction of sodium persulfate (40 g/L) and sodium chlorite (80 g/L) under nitrogen bubbling for about 1 hr (Rougé et al., 2020; Wang et al., 2021b). KMnO_4 stock solution was prepared by dissolving KMnO_4 in ultrapure water. The pre-oxidants were dosed at 4 mg/L and AOM was dosed at 5 mg-C/L. The pH was controlled by phosphate buffer solution at 7.0. Reaction time was 10 min. The ozonated samples were stored at 4°C in the dark for no more than 24 hr before the chlorination experiment.

The chlorination experiments were carried out with 100 mL of the pre-oxidized solutions at pH 7.0 in amber glass bottles. The chlorinated samples were incubated at $25 \pm 1^\circ\text{C}$ in the dark for 3 days and then quenched for the DBP analysis.

1.3. Analytical methods

The total organic carbon (TOC) of AOM was detected by a TOC-V analyzer (Shimadzu, Japan). The concentrations of the formed DBPs were determined by Purge-and-trap gas chromatography-mass spectrometry (PT-GC-MS). The amino acids were examined by Hitachi L8900 automatic amino acid analyzer. The genotoxicity and cytotoxicity were calculated by the methods reported by Liu et al. (2018). CCA and Pearson's correlation analysis were carried out by SPSS statistics 26.0 software (IBM, Armonk, NY, USA). Data from 10 samples, including EOM, IOM and their pre-oxidated samples were applied for statistical tests. Analytical methods of EEM fluorescent and amino acids were described in Appendix A Text S3.

2. Results and discussion

2.1. Impact of pre-oxidation on AOM characterization

Molecular weight percentage of EOM and IOM were determined based on the TOC data and shown in Fig. 1. After pre-

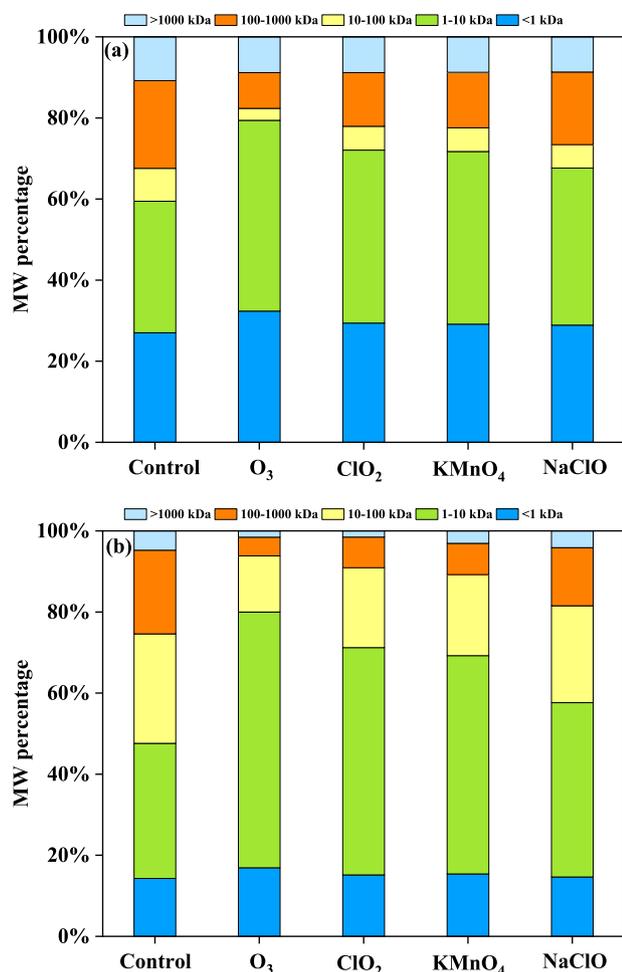


Fig. 1 – Distribution of each MW fraction in DOC of (a) EOM and (b) IOM derived from *M.aeruginosa*. Experimental conditions: TOC = 5 mg-C/L, oxidants doses were 4 mg/L, pH=7.

oxidation, the proportion of low-MW (MW < 10 kDa) fractions increased to different degrees. The maximum variations on low-MW fraction were caused by pre-ozonation, which were 19.95% of EOM and 32.38% of IOM, and relatively slighter increment of low-MW fraction were observed when other pre-oxidants were used. Of note, the variations can be attributed to the oxidizing property of oxidants, which were usually characterized by oxidation-reduction potential (ORP) (Appendix A Table S1). The ORP of these oxidants were ordered as O₃>KMnO₄≈ClO₂>NaClO, and oxidant with higher ORP resulted in a more obvious variation on AOM characterization.

The EEM scanning were performed on AOM and their pre-oxidated samples, and for quantitative comparison, their average fluorescent intensity (AFI) values for four regional components were calculated and shown in Fig. 2. Four regional fluorescent spectra were determined based on their excitation/emission wavelengths (Chen et al., 2003). The regions represent the fulvic- (FA), soluble microbial product- (SMP), aromatic protein- (AP) and humic- (HA) like substances. Pre-oxidation caused decrease on AP and SMP, while increased FA. As reported by Hua et al. (2019a), AP and SMP were most abun-

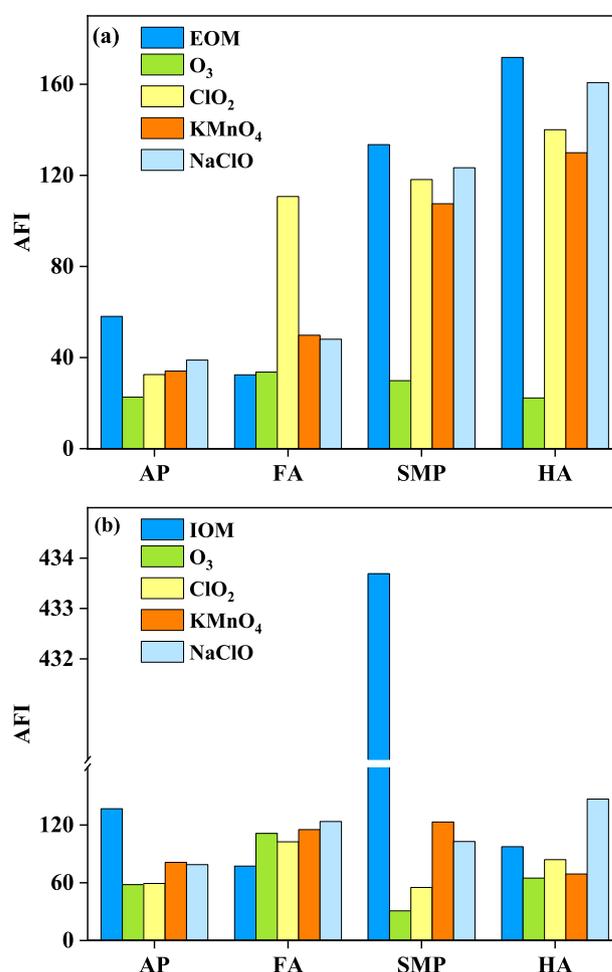


Fig. 2 – Variations of calculated regional AFI percentages within the pre-oxidations of (a) EOM and (b) IOM. Experimental conditions: TOC = 5 mg-C/L, oxidants doses were 4 mg /L, pH=7.

dant in high-MW fractions of AOM, while FA and HA became the main components in low-MW fractions of AOM. The result indicated that organic matters with high-MW tend to be degraded in pre-oxidation process, which was consistent with the molecular weight fraction variation. It is worth noting that after pre-oxidated by NaClO, the intensity of some components, such as FA of EOM, FA and HA of IOM increased. This could be attributed to that NaClO degraded high-MW organic matters to HA and FA, while it could not further degrade HA and FA because of the relatively weak oxidizing ability.

To further understand the variation of specific molecules in AOM, amino acids, a group of typical N-DBPs precursors were taken as examples. Fig. 3 shows the detected amino acids in and their concentration in IOM and its oxidized samples. The total concentration of amino acids decreased after pre-oxidation, which further proved that molecules in AOM have been decomposed. Of note, as reported by Fang et al. (2010), tryptophan, tyrosine, phenylalanine and histidine were the essential aromatic proteins in algal cells, and the concentration of tyrosine and phenylalanine detected in our samples decreased after pre-oxidation, which was consistent

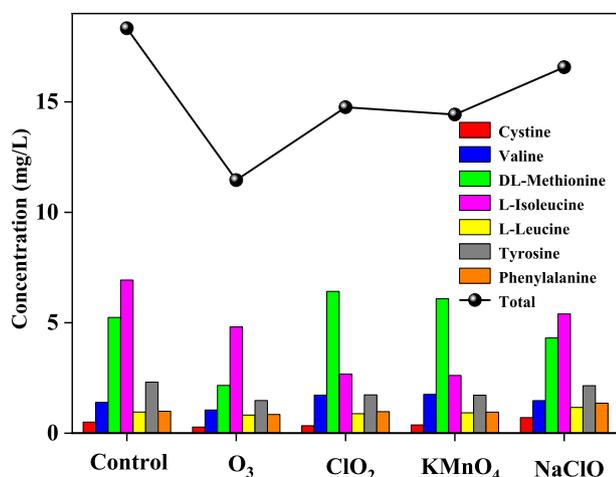


Fig. 3 – Variations of amino acids concentration within the pre-oxidations of IOM. Experimental conditions: TOC = 5 mg-C/L, oxidants doses were 4 mg /L, pH=7.

with the phenomenon that the intensity of AP component decreased.

2.2. DBP formation after pre-oxidation

Fig. 4 shows the AOM-derived DBP formation after pre-oxidation during subsequent chlorination. As reported by Hua et al. (2019a), TCM was the major THMs (> 98% of total THMs), while DCAA and TCAA were the major HAAs. Thus TCM, DCAA and TCAA were regarded as the major C-DBPs, while DCAN and TCNM were used to stand for N-DBPs in our study. In general, pre-ozonation increased formation of detected DBPs to different degrees compared to the control sample. The most significant variation happened on the formation of TCNM, pre-ozonation increased which by 20 times and 10 times higher of EOM and IOM, respectively. The phenomenon could be attributed to the fact that organic-N (e.g. proteins) in AOM were degraded to nitro compounds (e.g. aminophenols) by ozone (Zhu et al., 2015), and amino acids were decomposed to smaller N-containing molecules (Fig. 3), which were favorable to form TCNM during chlorination. Besides, the TCM and DCAA formation also increased, which were 270% and 202% of EOM, and 189% and 241% of IOM, respectively.

When pre-treated by NaClO, formation of N-DBPs decreased by 51% while formation of C-DBPs increased by 46% during subsequent chlorination. Specifically, the formation of DCAA and TCAA increased by 46% and 44% of EOM, and 52% and 46% of IOM, respectively. The formation of DCAN decreased by 107% and 25% of EOM and IOM, respectively. Compared to O₃, NaClO was much less efficient to decompose organic matters, resulting in less precursors which were favorable to form DBPs generated. This was further confirmed by the detected amino acids concentration (Fig. 3), which only decreased by 10% when NaClO treated, while decreased by 38% when O₃ treated.

Formation of most DBPs changed more slightly after pre-oxidated by ClO₂ and KMnO₄ than O₃. It should be noted that

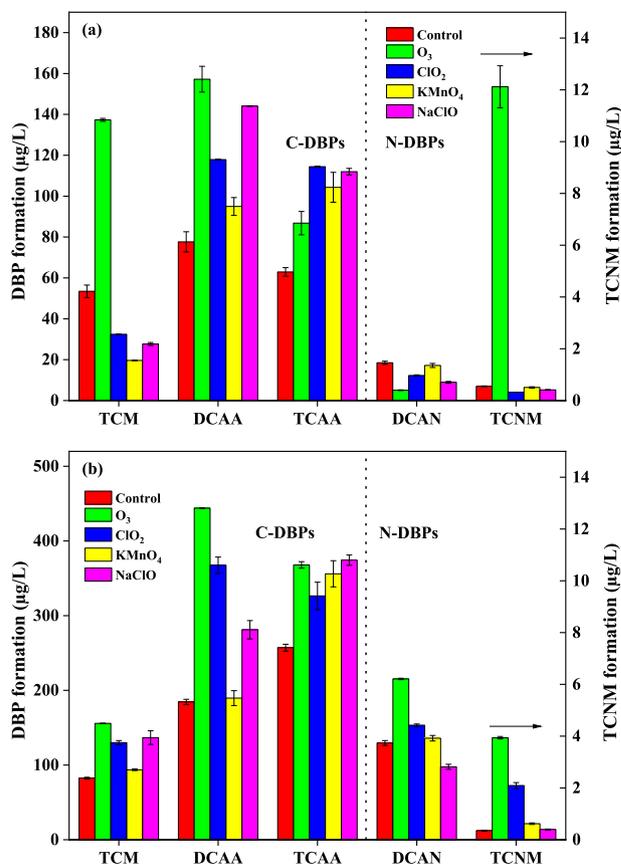


Fig. 4 – Variations of DBPFP derived from each pre-oxidated and the original (a) EOM and (b) IOM. Chlorination conditions: TOC = 5 mg-C/L, oxidants doses were 4 mg/L, pH=7, 3 days, 25±1°C. Error bars represent one standard deviation of duplicate measurements.

the formation of TCNM increased by 499% when IOM was pre-treated by ClO₂. The phenomenon indicated that AOM pre-treated by strong oxidizer like O₃ and ClO₂ could massively increase the formation of TCNM (Liu et al., 2017).

In summary, the formation of most DBPs during chlorination of AOM increased after pre-oxidation. The levels were highly dependent on the oxidizing ability of oxidants.

2.3. Relationship between Fluorescent/MW and AOM-derived DBP formation

To further understand the relationship between characteristic parameters and DBP formation, CCA analysis and Pearson's correlation analysis were performed based on the 10 samples (EOM, IOM and their pre-oxidated samples). Fig. 5 shows the CCA ordination biplot for EEM components and DBPs. The CCA test indicated that the formation of DCAA and TCAA had a positive correlation with AP component, while TCM had a positive correlation with FA component. As reported by Hua et al. (2019a), AP components in IOM were favorable precursors of HAAs and low-MW IOM like FA had higher tendency to form THMs. Our results supported the previous findings using different samples and further confirmed that EOM also

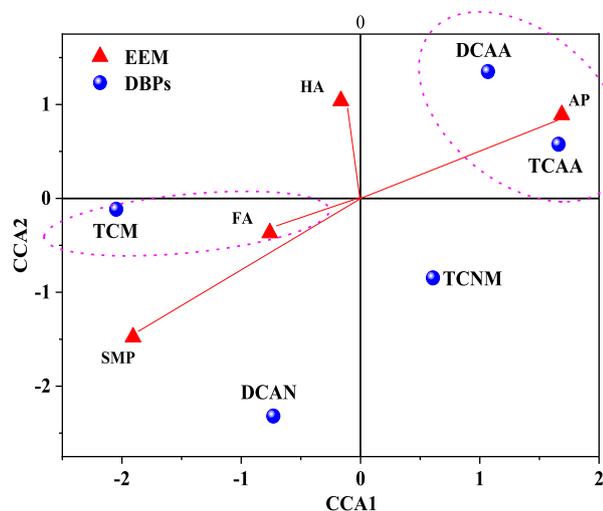


Fig. 5 – CCA ordination biplot for DBPFP and fluorescent EEM components (HA, FA, SMP, AP).

had the same properties. However, it could be observed that N-DBPs, including TCNM and DCAN, were not strongly dependent on fluorescent properties.

Appendix A Table S2 summarized the Pearson's correlation of each MW fraction and DBP formation potential. Significant correlations ($p < 0.05$) were only observed in MW fractions and N-DBPs. DCAN and TCNM had positive correlations with fraction of MW < 1 kDa, the coefficients of which were 0.900 and 0.903, respectively. Furthermore, TCNM had a negative correlation with fraction of MW between 100 - 1000 kDa, the coefficient of which was -0.894. The result indicated that low-MW fractions were favorable to form N-DBPs, which was consistent with the phenomenon observed in Fig. 4 that TCNM increased greatly after pre-ozonation.

2.4. Toxicity of DBPs after pre-oxidation

The theoretical cytotoxicity and genotoxicity of DBPs generated from different samples were calculated and shown in Fig. 6, and toxicity of each DBP was shown in Appendix A Fig. S3. After pre-oxidation, both cytotoxicity and genotoxicity of all samples increased. Among the four pre-oxidants, ozone pre-treatment increased the toxicity of all samples most significantly in subsequent chlorination. Ozone pre-treatment increased cytotoxicity and genotoxicity of IOM by 70.5% and 103.3%, and EOM by 101.0% and 355.7%, respectively. The phenomenon can be explained by that nearly all concentration of DBPs increased when ozone pre-oxidation was performed. Although some DBP formation decreased when other pre-oxidants were used (e.g. TCM in Fig. 3a), the toxicity of samples still increased overall. The reason was that TCAA ($LC_{50} = 0.0024$ M) and TCNM (SCGE genotoxic potency = 0.0000934) were the main contributors to cytotoxicity and genotoxicity, respectively (Appendix A Fig. S3), and the concentration of TCAA and TCNM increased with all pre-oxidation treatments.

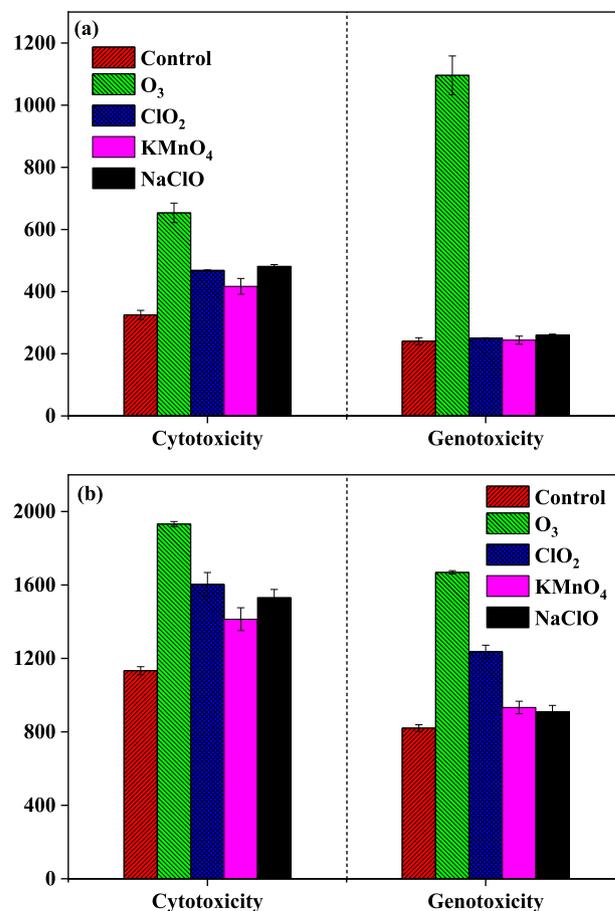


Fig. 6 – The calculated cytotoxicity and genotoxicity of DBPs generated from pre-oxidized and original (a) EOM and (b) IOM in chlorination. Chlorination conditions: TOC = 5 mg-C/L, oxidants doses were 4 mg/L, pH=7, 3 days, 25±1°C. Error bars represent one standard deviation of duplicate measurements.

2.5. Implications for drinking water treatment

Pre-oxidation has been proved to be an effective way to remove algal cells by coagulation-sedimentation (Xie et al., 2013). However, the damaged algal cells could release AOM, which contained large amount of DBP precursors, algal toxins and odors, leading to the deterioration of water quality (Henderson et al., 2008a). Furthermore, AOM could also be degraded in the pre-treatment process and result in the increment of the formation of some high toxic DBPs in subsequent chlorination. Overall, after pre-oxidation, both cytotoxicity and genotoxicity of the tested samples increased to different degrees. Compared to O₃, KMnO₄, ClO₂ and NaClO were better pre-oxidants because they increased significantly less to the toxicity of water samples. Meanwhile, KMnO₄ and ClO₂ pre-oxidations were efficient ways to enhance algae removal. Thus, KMnO₄ and ClO₂ could be good options for removing algal cells as well as limiting DBP formation.

3. Conclusions

The influence of pre-oxidation on AOM characterization properties and AOM-derived DBP formation were studied. The CCA analysis and Pearman's correlation analysis were used to analyze the relationship between characterization parameters and DBP formation. The following conclusions can be drawn.

- (1) AOM-derived C-DBPs are strongly dependent on fluorescent. AP component have a positive correlation with HAAs and FA component have a positive correlation with TCM.
- (2) AOM-derived N-DBPs are closely associated with low-MW (< 1 kDa) fractions, and TCNM formation have a negative correlation with fraction of MW between 100 - 1000 kDa.
- (3) Pre-oxidation would significantly increase both cytotoxicity and genotoxicity of AOM during subsequent chlorination. KMnO_4 and ClO_2 are better choice for removing algal cells as well as limiting DBP formation compared to O_3 and NaClO .

Acknowledgments

This work was supported by the National Natural Science Foundation (Nos. 51878257, 52100007), the Natural Science Foundation of Hunan Province (No. 2021JJ40066) and the Natural Science Foundation of Hunan Province (No. 2021JJ40106).

Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2021.12.021.

REFERENCES

- Chen, W., Westerhoff, P., Leenheer, J.A., Booksh, K., 2003. Fluorescence excitation–emission matrix regional integration to quantify spectra for dissolved organic matter. *Environ. Sci. Technol.* 37 (24), 5701–5710.
- Chen, Y., Bai, F., Li, Z., Xie, P., Wang, Z., Feng, X., et al., 2020. UV-assisted chlorination of algae-laden water: cell lysis and disinfection byproducts formation. *Chem. Eng. J.* 383, 123165.
- Coral, L.A., Zamyadi, A., Barbeau, B., Bassetti, F.J., Lapolli, F.R., Prevost, M., 2013. Oxidation of *Microcystis aeruginosa* and *Anabaena flos-aquae* by ozone: Impacts on cell integrity and chlorination by-product formation. *Water Res.* 47 (9), 2983–2994.
- Dong, F., Lin, Q., Li, C., He, G., Deng, Y., 2021. Impacts of pre-oxidation on the formation of disinfection byproducts from algal organic matter in subsequent chlor(am)ination: a review. *Sci. Total Environ.* 754, 141955.
- Dong, F., Liu, J., Li, C., Lin, Q., Zhang, T., Zhang, K., Sharma, V.K., 2019. Ferrate(VI) pre-treatment and subsequent chlorination of blue-green algae: quantification of disinfection byproducts. *Environ. Int.* 133, 105195.
- Fang, J., Yang, X., Ma, J., Shang, C., Zhao, Q., 2010. Characterization of algal organic matter and formation of DBPs from chlor(am)ination. *Water Res.* 44 (20), 5897–5906.
- Guo, T., Yang, Y., Liu, R., Li, X., 2017. Enhanced removal of intracellular organic matters (IOM) from *Microcystis aeruginosa* by aluminum coagulation. *Sep. Purif. Technol.* 189, 279–287.
- Henderson, R., Parsons, S.A., Jefferson, B., 2008a. The impact of algal properties and pre-oxidation on solid–liquid separation of algae. *Water Res.* 42 (8), 1827–1845.
- Henderson, R.K., Baker, A., Parsons, S.A., Jefferson, B., 2008b. Characterisation of algogenic organic matter extracted from cyanobacteria, green algae and diatoms. *Water Res.* 42 (13), 3435–3445.
- Hong, H.C., Huang, F.Q., Wang, F.Y., Ding, L.X., Lin, H.J., Liang, Y., 2013. Properties of sediment NOM collected from a drinking water reservoir in South China, and its association with THMs and HAAs formation. *J. Hydrol.* 476, 274–279.
- Hua, G., Reckhow, D.A., 2007. Comparison of disinfection byproduct formation from chlorine and alternative disinfectants. *Water Res.* 41 (8), 1667–1678.
- Hua, L.C., Chao, S.J., Huang, C., 2019a. Fluorescent and molecular weight dependence of THM and HAA formation from intracellular algogenic organic matter (IOM). *Water Res.* 148, 231–238.
- Hua, L.C., Lai, C.H., Wang, G.S., Lin, T.-F., Huang, C., 2019b. Algogenic organic matter derived DBPs: precursor characterization, formation, and future perspectives – a review. *Crit. Rev. Env. Sci. Tec.* 49 (19), 1803–1834.
- Jia, P., Zhou, Y., Zhang, X., Zhang, Y., Dai, R., 2018. Cyanobacterium removal and control of algal organic matter (AOM) release by UV/ H_2O_2 pre-oxidation enhanced Fe(II) coagulation. *Water Res.* 131, 122–130.
- Lee, H., Lim, J., Zhan, M., Hong, S., 2019. UV-LED/PMS preoxidation to control fouling caused by harmful marine algae in the UF pretreatment of seawater desalination. *Desalination* 467, 219–228.
- Li, M., Qiang, Z., Bolton, J.R., Li, W., Chen, P., 2014. UV disinfection of secondary water supply: Online monitoring with micro-fluorescent silica detectors. *Chem. Eng. J.* 255, 165–170.
- Liu, C., Ersan, M.S., Plewa, M.J., Amy, G., Karanfil, T., 2018. Formation of regulated and unregulated disinfection byproducts during chlorination of algal organic matter extracted from freshwater and marine algae. *Water Res.* 142, 313–324.
- Liu, R., Guo, T., Ma, M., Yan, M., Qi, J., Hu, C., et al., 2019. Preferential binding between intracellular organic matters and Al13 polymer to enhance coagulation performance. *J. Environ. Sci.* 76, 1–11.
- Liu, Z., Chen, W., Yu, H., Tao, H., Xu, H., Yu, J., et al., 2017. Effects of pre-oxidation and adsorption on haloacetonitrile and trichloronitromethane formation during subsequent chlorination. *Environ. Sci. Pollut. R* 24 (27), 21836–21845.
- Ma, M., Wang, M., Cao, X., Li, Y., Gu, J., 2019. Yield of trihalomethane, haloacetic acid and chloral upon chlorinating algae after coagulation-filtration: Is pre-oxidation necessarily negative for disinfection by-product control? *J. Hazard. Mater.* 364, 762–769.
- Naceradska, J., Pivokonsky, M., Pivokonska, L., Baresova, M., Henderson, R.K., Zamyadi, A., et al., 2017. The impact of pre-oxidation with potassium permanganate on cyanobacterial organic matter removal by coagulation. *Water Res.* 114, 42–49.
- Pivokonsky, M., Kloucek, O., Pivokonska, L., 2006. Evaluation of the production, composition and aluminum and iron complexation of algogenic organic matter. *Water Res.* 40 (16), 3045–3052.
- Plummer, J.D., Edzwald, J.K., 2001. Effect of Ozone on Algae as Precursors for Trihalomethane and Haloacetic Acid Production. *Environ. Sci. Technol.* 35 (18), 3661–3668.
- Rickman, M., Pellegrino, J., Hock, J., Shaw, S., Freeman, B., 2013.

- Life-cycle and techno-economic analysis of utility-connected algae systems. *Algal Res.* 2 (1), 59–65.
- Rougé, V., von Gunten, U., Lafont de Sentenac, M., Massi, M., Wright, P.J., Croué, J.P., et al., 2020. Comparison of the impact of ozone, chlorine dioxide, ferrate and permanganate pre-oxidation on organic disinfection byproduct formation during post-chlorination. *Environ. Sci.* 6 (9), 2382–2395.
- Sheng, D., Bu, L., Zhu, S., Wu, Y., Wang, J., Zhou, S., 2021. Organic chloramines formation from algal organic matters: Insights from Fourier transform-ion cyclotron resonance mass spectrometry. *Water Res.* 206, 117746.
- Shi, X., Bi, R., Yuan, B., Liao, X., Zhou, Z., Li, F., et al., 2019. A comparison of trichloromethane formation from two algae species during two pre-oxidation-coagulation-chlorination processes. *Sci. Total Environ.* 656, 1063–1070.
- Tomlinson, A., Drikas, M., Brookes, J.D., 2016. The role of phytoplankton as pre-cursors for disinfection by-product formation upon chlorination. *Water Res.* 102, 229–240.
- Wan, Y., Xie, P., Wang, Z., Ding, J., Wang, J., Wang, S., et al., 2019. Comparative study on the pretreatment of algae-laden water by UV/persulfate, UV/chlorine, and UV/H₂O₂: Variation of characteristics and alleviation of ultrafiltration membrane fouling. *Water Res.* 158, 213–226.
- Wang, B., Zhang, Y., Qin, Y., Li, H., 2021a. Removal of *Microcystis aeruginosa* and control of algal organic matter by Fe(II)/peroxymonosulfate pre-oxidation enhanced coagulation. *Chem. Eng. J.* 403, 126381.
- Wang, C., Wu, Y., Wang, Y., Bai, L., Jiang, H., Yu, J., 2018. Lanthanum-modified drinking water treatment residue for initial rapid and long-term equilibrium phosphorus immobilization to control eutrophication. *Water Res.* 137, 173–183.
- Wang, J., Wu, Y., Bu, L., Zhu, S., Zhang, W., Zhou, S., Gao, N., 2021b. Simultaneous removal of chlorite and contaminants of emerging concern under UV photolysis: Hydroxyl radicals vs. chlorate formation. *Water Res.* 190, 116708.
- Wert, E.C., Rosario-Ortiz, F.L., 2013. Intracellular organic matter from cyanobacteria as a precursor for carbonaceous and nitrogenous disinfection byproducts. *Environ. Sci. Technol.* 47 (12), 6332–6340.
- Xie, P., Ma, J., Fang, J., Guan, Y., Yue, S., Li, X., et al., 2013. Comparison of permanganate preoxidation and preozonation on algae containing water: cell integrity, characteristics, and chlorinated disinfection byproduct formation. *Environ. Sci. Technol.* 47 (24), 14051–14061.
- Zhou, S., Zhu, S., Shao, Y., Gao, N., 2015. Characteristics of C-, N-DBPs formation from algal organic matter: role of molecular weight fractions and impacts of pre-ozonation. *Water Res.* 72, 381–390.
- Zhu, M., Gao, N., Chu, W., Zhou, S., Zhang, Z., Xu, Y., et al., 2015. Impact of pre-ozonation on disinfection by-product formation and speciation from chlor(am)ination of algal organic matter of *Microcystis aeruginosa*. *Ecotox. Environ. Safe.* 120, 256–262.