# OCCURRENCE OF CHLOROPHENOL COMPOUNDS IN AQUATIC ENVIRONMENTS OF CHINA AND EFFECT OF SUSPENDED PARTICLES ON TOXICITY OF THESE CHEMICALS TO AQUATIC ORGANISMS: A REVIEW

WANG, Y. Z.[1,2] – ZHANG, S. L.[1] – XU, W.[1] – CUI, W. Y.[1*] – ZHANG, J.[1*]

[1]*Monitoring and Scientific Research Center of Ecology and Environment, Supervision and Administration of Ecology and Environment of Haihe River Basin and North China Sea, Ministry of Ecology and Environment of People's Republic of China, Tianjin 300170, China*

[2]*Key Lab of Basin Water Resource and Eco-Environmental Science in Hubei Province, Wuhan 430010, China*

**Corresponding authors*
*e-mail: wenyancui@sohu.com; zhangjun506@163.com*

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**Abstract.** Chlorophenol compounds have received widespread attention because of their sources, applications and characteristics. As an important environmental medium, suspended particles are ubiquitously distributed in aquatic ecosystems. In order to investigate the occurrence of chlorophenol compounds in aquatic environments of China and their toxicity in the case of suspended particles, literature retrieval methods were used to analyze their presence in waters, sediments and organisms in China and the effect of suspended particles on their toxicity to aquatic organisms was also investigated. The results showed that pentachlorophenol (PCP) or NaPCP present ubiquitous pollution and distributions in various aquatic environments. Meanwhile, in order to better protect human health and aquatic organisms, considering the effects of suspended particles on toxicity of these chemicals towards aquatic organisms, appropriate standards for chlorophenols were needed.

**Keywords:** *pollution, distribution, chemical toxicity, water quality criteria, environmental protection*

## Introduction

The occurrence and ecotoxicity of the persistent organic pollutants (POPs) are particular issues in environmental governance. As a group of aromatic compounds with high toxicity and carcinogenic characteristics, chlorophenol compounds are one of the typical POPs and can be persistently present in the environment (Garba et al., 2019). The entrance of chlorophenol compounds into the aquatic environments mainly results from industrial, domestic and agricultural activities (Czaplicka, 2004; Vlastos et al., 2016), particularly the industrial wastewater discharge from pesticide plants, refineries, wood and paper mills (Tarighian et al., 2003; Olaniran and Igbinosa, 2011). These compounds have been intensively studied especially 2, 4-dichlorophenol(2, 4-DCP), 2,4,6-trichlorophenol(2,4,6-TCP) and pentachlorophenol (PCP) (Jin et al., 2010), and the other compounds such as 2-chlorophenol(2-CP), 2, 6-dichlorophenol(2, 6-DCP), 2,3,5-trichlorophenol(2,3,5-TCP), which were also detected in some water environment (Wu et al., 2012a, b, c). PCP has been evaluated as an environmental endocrine disruptor according to the existing research (Zha et al., 2006), and also has been listed as a priority contaminant by the U.S. Environmental Protection Agency due to the toxicity and associated risks.


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Chlorophenol compounds have received intensive concern due to their widespread distribution and toxicity on humans and organisms that are exposure to chemical compounds in the environment, particularly in aquatic environments. Because of their strong toxicity, endocrine interference effect, mutagenicity, carcinogenicity and bioaccumulation (Muir and Eduljee, 1999; Yu et al., 2019), it is essential to obtain the pollution and distribution of chlorophenol compounds in aquatic environments of China and study the ecotoxicity to aquatic organisms for the prevention and control of their contamination. Information about pollution conditions of chlorophenol compounds could be obtained and analyzed from published articles related to chlorophenols found in different environmental media by literature retrieval, classification and analysis. Ecotoxicity of chlorophenol compounds to aquatic organisms could be conducted by toxicity experiments as shown in several previous studies (Zhang et al., 2008; Xing et al., 2012; Li et al., 2014; Chen et al., 2016; Ge et al., 2017; Yu et al., 2019), and then their effects and risk to aquatic organisms could be effectively evaluated based on the concentrations and distributions of chlorophenol compounds in aquatic environments and the acute toxicity or chronic toxicity data.

Suspended particles are widely distributed in aquatic ecosystems, and the suspended particles entering into waterbodies mainly come from the process of surface runoff from terrestrial ecosystems. Their concentrations in lakes or rivers are generally between 10 $\mu g \cdot L^{-1}$ and several hundred, or even up to several hundred $g \cdot L^{-1}$ (Boenigk et al., 2005). According to previous research, the time that suspended particles concentration exceeded 258 $mg \cdot L^{-1}$ in Taihu lake was more than 125 days (Zhu et al., 2005). Suspended particles are an important environmental factor that can play an important role in regulating pollutants toxicity to aquatic organisms (Ma et al.,2002). It is generally considered that suspended particles can change the bioavailability of chemicals through sorption processes, particularly, of the hydrophobic organic chemicals and heavy metals (Herbrandson et al., 2003a; Yang et al., 2006). In fact, suspended particles themselves also could influence aquatic organisms (Kirk and Gilber, 1990; Kirk, 1991). Kirk and Gilber (1990, 1991) demonstrated that suspended particles have acute toxicity to several species of planktonic rotifers and cladocerans. The survival of *Daphnia pulex* was significantly influenced while the concentration of suspended particles was 50 and 100 $mg \cdot L^{-1}$ respectively, and suspended particles concentration showed an inverse correlation with the reproduction, growth of *Daphnia magna*, and also with the survival of its larvae. Thus, suspended particles could increase stress on aquatic organisms in survival conditions or decrease the exposure conditions of chemicals by adsorption, and then the external stress could affect the toxicodynamic response of aquatic organisms to chemicals (Herbrandson et al., 2003a, b).

It should be noted that water quality standards or criteria were usually originated from toxicology experiment data. However, toxicity experiments on aquatic organisms to calculate acute toxicity or chronic toxicity data are normally carried out under laboratory conditions according to previous reports. The water used in the experiments generally is tap water or synthetic water which has a low ionic strength, simple inorganic chemistry, stable value of pH and temperature, and contain low amounts of suspended particles and dissolved organic matters (Yilmaz et al., 2004; Selviet al., 2005; Mihaich et al., 2009). The toxicity of chemicals to aquatic organisms can be modified by water hardness, pH, temperature, suspended particles, and dissolved organic matter. For example, previous research indicated that hardness and pH could change heavy metal toxic effects to aquatic species (Long et al., 2004), and pH could


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affect chlorophenol's toxicity to green algae in the presence and absence of humic acid (Suzuki and Shoji, 2020). Bejarano et al. (2005) indicated that dissolved organic matters generally reduced chlorothalonil and chlorpyrifos toxicity to *Amphiascus tenuiremis* due to the decrease of bioavailability, while significantly enhancing the acute toxicity of fipronil because of the reduced light-dependent formation of fipronil-desulfinyl, a light or equivalently toxic metabolite. It is apparent that there are certain limitations that prevent us from protecting aquatic organisms caused by a lethal concentration of pollutants according to laboratory standard methods. Based on our review on the occurrence of chlorophenol compounds in aquatic environments of China and effects of suspended particles on toxicity of these chemicals to aquatic organisms, the results can be used as scientific basis for the toxic effect assessment of chlorophenol compounds to aquatic organisms and the development of water quality standards and criteria for better environmental protection.

## Study methods

Literature retrieval methods are frequently used to collect sufficient and effective literatures from database according to the key words and setting time interval. In this study, these methods were used to summarize the literatures about the occurrence of chlorophenol compounds in aquatic environments of China including water, sediments and aquatic organisms in SCI journals and Chinese journals published from 1990 to 2019. Specific rivers or lakes, media, sampling date, levels and sources of chlorophenol compounds were mainly focused in this section. Literatures about the toxicity of these chemicals to aquatic organisms, including the effects of suspended particles on toxicity, were also concerned in the same time interval. Key words included China, chlorophenols, 2,4-dichlorophenol/2,4-DCP, 2,4,6-trichlorophenol/2,4,6-TCP, pentachlorophenol/PCP, toxicity and suspended particles/suspended solids, both retrieved separately and combined with the following terms including environments, rivers, lakes, waters, sediments, fish and aquatic organisms. Other available data and relevant information were from literature search. The obtained literatures were classified and analysed according to the target of each sub-chapter of the paper.

## Results and analysis

### *Pollution and distributions of chlorophenol compounds in surface waters of China*

Three literatures about the occurrence of chlorophenol compounds in surface water of rivers or lakes in China were found in SCI journals and nine literatures of that in Chinese journals. As shown in *Table 1*, PCP could be detected in all water environments of main rivers or lakes in China, which reflected that PCP are main chlorophenol pollutants. Concentrations of PCP showed significant difference in important rivers and lakes. The highest residue appeared in Dongting lake. However, it can be certain that the PCP pollution in surface water of the Dongting Lake tends to decrease gradually according to the data reported by Feng et al. (2014) in recent years. Gao et al. (2008) summarized the pollution levels of chlorophenols including 2, 4-DCP, 2, 4, 6-TCP and PCP in seven watershed of China. The results indicated that PCP was the most common chlorophenol in 85.4% of samples (median: 50.0 $ng \cdot L^{-1}$, range from 1.1 to 594 $ng \cdot L^{-1}$) and PCP contamination in the Yangtse River was the most serious


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because of frequent industrial wastewater discharge and widely historical use of pesticide for killing snails in this schistosomiasis epidemic watershed. While the rivers with high 2,4-DCP and 2,4,6-TCP levels mainly occurred in the Yellow River, which may be for the reason that 2,4-DCP and 2,4,6-TCP originate from degradation processes of industrial activities or phenoxyacid herbicides that were extensively used in agricultural areas of these basin.

***Table 1.*** *The occurrence of chlorophenol compounds in surface waters of China*

| Location | Date | Sampling number | Compound | Levels ($ng·L^{-1}$) Range | Levels ($ng·L^{-1}$) Mean | Main source | Reference |
|---|---|---|---|---|---|---|---|
| Haihe River | — | 10 | PCP | ND~1800.00 | 189.00 | Production and sewage discharge | Liu et al., 2006 |
| Dongting Lake | 1998 | 8 | PCP | <5.00~103700.00 | 14949.79 | Historical use | Zheng et al., 2000; Zhang et al., 2001 |
| Qiantang River | 2005 | 35 | 2,4-DCP and 2,4,6-TCP | — | 876.86[a] | Historical use | Chen et al., 2005 |
| Pearl River | 2007 | 5 | 2-CP, 2,4-DCP, 2,4,6-TCP and PCP | 41.20~54.40[a] | 46.52[a] | Wastewater | Dong et al., 2009 |
| Hengmen River | | | | 67.60~128.20[a] | 86.72[a] | | |
| Fish pond | | | | 6.90~19.10[a] | 12.66[a] | | |
| Songhuajiang River | 2008 | 40 | PCP | < 1.10~70.00 | — | — | Gao et al., 2008 |
| | | | 2,4-DCP | < 1.10~250.00 | — | | |
| | | | 2,4,6-TCP | < 1.40~250.00 | — | | |
| Liaohe River | | 58 | PCP | < 1.10~60.00 | — | | |
| | | | 2,4-DCP | < 1.10~170.00 | — | | |
| | | | 2,4,6-TCP | < 1.40~30.00 | — | | |
| Haihe River | | 39 | PCP | 50.00~70.00 | — | | |
| | | | 2,4-DCP | < 1.10~40.00 | — | | |
| | | | 2,4,6-TCP | 10.00~40.00 | — | | |
| Yellow River | | 50 | PCP | < 1.10~70.00 | — | | |
| | | | 2,4-DCP | < 1.10~19960.00 | — | | |
| | | | 2,4,6-TCP | < 1.40~28650.00 | — | | |
| Yangtze River | | 150 | PCP | < 1.10~594.00 | — | | |
| | | | 2,4-DCP | < 1.10~380.00 | — | | |
| | | | 2,4,6-TCP | < 1.40~30.00 | — | | |
| Huaihe River | | 39 | PCP | < 1.10~351.00 | — | | |
| | | | 2,4-DCP | < 1.10~246.00 | — | | |
| | | | 2,4,6-TCP | < 1.40~70.00 | — | | |
| Pearl River | | 150 | PCP | < 1.10~396.00 | — | | |
| | | | 2,4-DCP | < 1.10~264.00 | — | | |
| | | | 2,4,6-TCP | < 1.40~70.00 | — | | |
| Southeast drainage area rivers | | 74 | PCP | < 1.10~32.40 | — | | |
| | | | 2,4-DCP | < 1.10~26.60 | — | | |
| | | | 2,4,6-TCP | < 1.40~22.00 | — | | |
| Northwest drainage area rivers | | 18 | PCP | < 1.10~60.00 | — | | |
| | | | 2,4-DCP | < 1.10~55.00 | — | | |
| | | | 2,4,6-TCP | < 1.40~69.50 | — | | |
| Southwest drainage area rivers | | 5 | PCP | < 1.10 | — | | |
| | | | 2,4-DCP | < 1.10 | — | | |
| | | | 2,4,6-TCP | < 1.40 | — | | |
| Yangtze River | 2009 | 8 | PCP | ND~220.00 | — | Historical use | Han et al., 2009 |
| | | | 2,4-DCP | ND~130.00 | — | | |


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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Songli spillway | 2010 | 7 | PCP, 2-CP, 2,4-DCP, 2,6-DCP,2,4,5-TCP,2,4,6-TCP, 2,4,5-TCP, 2,3,4,6-TECP and 2,3,5,6-TECP | 12.19~2386.90[a] | | Historical use | Wu et al., 2012a |
| Ouchi River | | 10 | | 2.50~691.00[a] | | | |
| Tuojiang River | | 10 | | 17.18~6148.28[a] | | | |
| Three Gorges Reservoir (Mainstream) | 2010 | 9 | 2,4-DCP, 2,6-DCP, 2,4,5-TCP,2,4,6-TCP, 2,3,4,5-TeCP and 2,3,4,6-TeCP | 1.82~16.10[a] | 5.23[a] | Wastewater | Wu et al., 2012b |
| Three Gorges Reservoir (tributaries) | | 55 | | 1.30~146.86[a] | 11.93[a] | | |
| Hangzhou Bay | 2013 | 18 | 19 chlorophenol compounds | 16.71~21810[a] | — | Wastewater | Qiu et al., 2016 |
| Dongting Lake | 2013 | 27 | PCP, 2,4,6-TCP, 2,3,4-TCP, | 19.75~111.49[a] | — | Historical use | Feng et al., 2014 |
| Yangtze River in Chongqin City | 2016 | 12 | PCP | ND~2370 | — | — | Yang et al., 2018 |
| Poyang Lake wetland | 2017 | 15 | PCP | 0.116~0.887 | 0.330 | Historical use | Yang et al., 2019 |
| Beitang Drainage River | 2018 | 7 | 4-CP, 2,5-DCP, 2,4-DCP, 2,6-DCP | ND~4.63 | — | Production and wastewater | Zhong et al., 2018 |
| Dagu Drainage River | | 16 | | ND~1.57 | — | | |
| Yongdingxin River | | 14 | | ND | — | | |

"—" stands for not reported. "a" indicates the total concentrations of the target compounds." ND" stands for not detected

### *Pollution and distributions of chlorophenol compounds in sediment environments of China*

As for the occurrence of chlorophenol compounds in sediment environment of rivers or lakes in China, five sources and eight articles were found in SCI journals and Chinese journals especially. As shown in *Table 2*, PCP was the main pollutant among chlorophenol compounds that were intensively reported in sediment environment of rivers or lakes in China, especially the pollutions of that in district of Yangtze River, Pearl River, Poyang Lake and Dongting Lake had generated great concern. Because of large amounts of PCP or NaPCP were used frequently and intensively historically in some area to control spread of snail borne schistosomiasis, or frequently used as a clean pond reagent in aquiculture areas, these phenomena were especially serious in Dongting Lake area. Due to the accumulation characteristics, sediment from Dongting Lake showed relatively higher PCP pollution levels than others, indicating an intensive history of pesticide usage in these areas. Pollution of chlorophenol compounds in sediment environment existed in many rivers or lakes in China, simultaneously the limited report on PCP levels around Jiaozhou Bay of Shandong province revealed their existence in coastal regions (Pan et al., 2008).

### *Pollution and distributions of chlorophenol compounds in organisms of China*

Limited information could be searched about the occurrence of chlorophenol compounds in fish or other organisms survived in rivers or lakes in China compared to them that in water and sediment environment. Only four articles were found about pollutions of PCP both showed in SCI journals and in Chinese journals. Because of PCP was usually used in fish ponds cleaning for killing mussels and shellfish in South China, the residual amount of PCP in aquatic organisms could reflect the PCP pollution levels in waters indirectly, and indicate possible risk from human exposure due to diet. So the PCP accumulation levels in aquatic organism samples including


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fish, shrimp, carp, crab and other aquatic organisms collected from fish ponds, farms or markets especially in Dongting Lake and Jiangsu province were detected. As shown in *Table 3,* Dongting Lake and Jiangsu province were the typical and key areas for long-term usage of NaPCP to clean ponds, which related to many literatures focused on these special districts, showed a much higher PCP presence in different aquatic organisms, such as fish, shrimp, frog, and so on. Similar to PCP pollution in water environment of the Dongting Lake, the pollution level of PCP in fish samples was also significantly reduced.

***Table 2.*** *The occurrence of chlorophenol compounds in sediment environment of China*

| Location | Date | Sampling number | Compound | Levels (ng·g$^{-1}$) | | Main source | Reference |
|---|---|---|---|---|---|---|---|
| | | | | Range | Mean | | |
| Yangtze River | — | 4 | PCP | 0.49~4.57 | — | Historic use | Xu et al., 2000 |
| Qingdao coastal sea | 1997, 1999 | 7 | PCP | ND~3.7 | 0.50 | Sewage sludge and historic use | Pan et al., 2008 |
| Dongting Lake | 1998 | 8 | PCP | 180.00~48300.00 | 20135.00 | Historic use | Zheng et al., 2000; Zhang et al., 2001 |
| Pearl River Delta | 2000~2001 | 7 | PCP | 1.44~ 34.40 | 7.93 | Historic use | Hong et al., 2005 |
| Yangtze River | 2005 | 11 | PCP | < 0.64~1.68 | 0.38 | Historic use | Tang et al., 2007 |
| Hanjiang River | | 4 | | < 0.64~0.87 | 0.34 | | |
| Fuhe River | | 3 | | < 0.64~0.77 | 0.46 | | |
| Sheshui River | | 1 | | 0.59 | 0.59 | | |
| Dongjing River | | 2 | | < 0.64~0.63 | — | | |
| Poyang Lake | 2006 | 4 | PCP | ND~23.80 | 20.75 | Historic use | Liu et al., 2008a |
| | | 19 | PCP | ND~35.28 | 26.61 | Historic use | Liu et al., 2008b |
| Aojiang River | 2006 | 6 | PCP | ND~71.40 | 27.76 | Historic use | Chen et al., 2008 |
| Taihu lake | 2008~2009 | 58 | 2,5-DCP | ND~116.80 | 26.90 | Industry and agriculture | Zhong et al., 2010 |
| | | | 2,4,6-TCP | ND~840.40 | 35.90 | | |
| | | | 2-CP | ND~166.10 | 6.00 | | |
| | | | 2,4-DCP | ND~143.10 | 19.60 | | |
| | | | 2,4.5-TCP | ND~65.30 | 14.60 | | |
| Huangpu River | 2010 | 13 | 2-CP, 3-CP, 4-CP, 2,6-DCP, 2,4-DCP, 2,5-DCP, 2,3-DCP, 3,5-DCP, 3,4-DCP, 2,4,6-TCP, 2,3,5-TCP, 2,3,4-TCP, 2,4,5-TCP, 2,3,6-TCP, 3,4,5-TCP, 2,3,5,6-TeCP, 2,3,4,5-TeCP, 2,3,4,6-TeCP and PCP | 3.79~47.10[a] | 18.30[a] | Human activities | Wu et al., 2012c |
| Suzhou River | | 5 | | 4.20~25.10[a] | 14.80[a] | | |
| Yunzao Brook | | 3 | | 3.64~5.48[a] | 4.44[a] | | |
| Yangtze River in Chongqin City | 2016 | 12 | PCP | ND~6.36 | — | — | Yang et al., 2018 |
| Poyang Lake wetland | 2017 | 15 | PCP | 0.062~0.0089 | 0.0234 | Historical use | Yang et al., 2019 |
| Beitang Drainage River | 2018 | 7 | 4-CP, 2-CP, 2,5-DCP, 3,4,5-TCP, PCP | ND~9.71 | — | Historical use | Zhong et al., 2018 |
| Dagu Drainage River | | 16 | | ND~65.1o | — | | |
| Yongdingxin River | | 14 | | ND | — | | |

"—" stands for not reported. "a" indicates the total concentrations of the target compounds." ND" stands for not detected


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***Table 3.*** *The occurrence of chlorophenol compounds in organisms of China*

| Location | Date | Sampling number | Organism | Compound | Levels ($ng \cdot g^{-1}$) Range | Levels ($ng \cdot g^{-1}$) Mean | Main source | Reference |
|---|---|---|---|---|---|---|---|---|
| Jiangsu Province | 1991~1993 | 2 | Fish | PCP | 0.02~2.13 | 0.15 | PCP usage | Yang et al., 1996 |
| Dongting Lake | 1998 | 8 | Silver carp (*Hypophthalmichthys molitrix*) | PCP | — | 550.00 | PCP usage | Zheng et al., 2000; Zhang et al., 2001 |
| | | | Grass carp *(Ctenopharyngodon Idellus)* | | — | 630.00 | | |
| | | | White bream *(Parabramis pekinensis)* | | 40.00~340.00 | 50.00 | | |
| | | | Common carp *(Cyprinus carpio)* | | 60.00~110.00 | 85.00 | | |
| Qingdao coastal sea | 1997, 1999 | 7 | Common Mussel *(Mytilus edulis Linee)* | PCP | — | 4.50 | Sewage sludge and historic use | Pan et al., 2008 |
| Jiangsu Province | 2003~2004 | 4 | Crucian carp *(Carassius auratus)* | PCP | — | 53.00 | PCP usage | Ge et al., 2007 |
| | | 6 | Grass carp *(Ctenopharyngodon idellus)* | | — | 3.60 | | |
| | | 4 | Big head carp *(Aristichthys nobilis)* | | — | 2.40 | | |
| | | 13 | Chinese mitten crab *(Eriocheir sinensis)* | | — | 0.90 | | |
| | | 1 | Silver carp *(Hypophthalmichthys molitrix)* | | — | 2.40 | | |
| | | 1 | Bull frog (*Rana catesbeiana)* | | — | 2.50 | | |
| | | 1 | Turtle *(Amyda sinensis)* | | — | 2.50 | | |
| | | 6 | Shrimp *(M. rosenbergii)* | | — | 1.00 | | |
| | | 13 | Shrimp *(M. nipponense)* | | — | 0.90 | | |
| | | 6 | Shrimp *(P. vanmamei)* | | — | 0.25 | | |
| Jiangsu Province | 2008 | 6 | Fish | PCP | 0.10~0.35 | 0.22 | PCP usage | Xu et al., 2010 |
| | 2009 | | | | 0.09~0.32 | 0.21 | | |
| Dongting Lake | 2013 | 27 | Common carp *(Cyprinus carpio)* | PCP | — | 92.33 | Historic use | Feng et al., 2014 |
| | | | Silver carp *(Hypophthalmichthys molitrix)* | | — | 87.76 | | |
| | | | White semiknife carp (*Ochetobius elongatus Kner*) | | — | 25.87 | | |
| | | | Crucian carp *(Carassius auratus)* | | — | 2.14 | | |

"—" stands for not reported

## *Effect of suspended particles on chlorophenols toxicity to aquatic organisms*

Aquatic organisms in natural waters are usually exposed to mixed pollutants and physical pressures, which could induce adverse effects such as behavioral, physiological or biochemical activity disturbance, and can even cause death. Suspended particles in natural waters are usually present and are the main stressors for aquatic organisms. Herbrandson et al. (2003b) and Zurek (1983) indicated that *Daphnia magna* could feed on suspended particles and the ingested particles may lead to decreased ability of daphnids to float in the water, causing a greater energy demand for extra effort and higher metabolism ability to maintain an appropriate position in the water area, and then


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played a role in toxicodynamics by increasing the energy requirements of the organisms, thus the suspended particles indirectly enhanced the toxicity of pollutants. Herbrandson, Bradbury and Swackhamer (2003a, b) demonstrated that suspended particles could influence carbofuran toxicokinetics in *Daphnia magna* and contribute to greater energy expenditures. Zurek (1983) found that *Daphnia hyaline* increased 10.6%~32.4% of their metabolism when exposed to a solution containing 100~1000 mg·$L^{-1}$ suspended particles and Kirk (1991) demonstrated that suspended clay sediment reduced the algal ingestion rate of *Daphnia ambigua* by 60%~70% and 27% respectively at low and high algal concentrations. The abnormal feeding activities induced by suspended particles can cause energy budget imbalance, which makes the organisms more fragile to additional pressures (Jeon et al., 2010). Furthermore, chemicals can enhance the toxicity to aquatic organisms through feeding on suspended particles with adsorbed chemicals (De Schamphelaere et al., 2007; De Schamphelaere and Janssen, 2004).

However, when the effect of suspended particles on chlorophenol compounds toxicity to aquatic organisms was focused, the above-mentioned theories were not applicable in some cases. Ra et al. (2008) investigated the acute toxicity of several pharmaceuticals, estrogens and phenols to *Daphnia magna* exposed to suspended particles containing humic acid, the results revealed that suspended particles did not adsorb pharmaceuticals and estrogens, as the toxicity of those chemicals exhibited no significant decreases to *Daphnia magna*, while the suspended particles adsorbed three phenolic compounds including octylphenol and pentachlorophenol, which promoted a significant toxicity decrease to *Daphnia magna*. As extremely important organisms in aquatic ecosystems, fish is widely distributed in the freshwater. Chemicals toxicity to fish could also be influenced by suspended particles. Yan et al. (2015) indicate that suspended particles (7500 and 15,000 mg/l) decreased dissolved chemicals by adsorption, thus decreasing atrazine toxicity to *Brachydanio rerio* (Zebrafish) through the reduction of bioavailability. The gill is an important organ that plays a vital role in respiration, and it is unquestionable that respiration (i.e. inhalation through gills) is the most significant way of pollutants exposure in water (Ge et al., 2017). A certain high concentration of suspended particles blocking the gills of fish may protect from the toxicity of chemicals.

In addition, the effect of suspended particles on aquatic organisms is dependent on several key factors including the concentrations, composition and particle size distribution of suspended particles, and also the duration of exposure to suspended particles (Bilotta and Brazier, 2008). Inorganic particles with sharp edges could stimulate the intestinal tract or externally-exposed tissues, leading to changes in energy resources allocation and food intake or respiratory rate reduction. Biochemical or behavioral reactions caused by the above stressors could imaginably aggravate the chemicals toxicity effects (Herbrandson et al., 2003b). Herbrandson et al. (2003b) demonstrated that suspended subsoil was more toxic than suspended decomposed peat to carbofuran exposed *Daphnia magna* and the main reason was that *Daphnia magna* required excessive amounts of energy to ingest suspended subsoil than suspended decomposed peat. The process of chemical poisoning to aquatic organisms is therefore more complex, particularly under natural conditions.

### *Comparison analysis of water quality criteria and chlorophenol compounds toxicity*

Water quality criteria is an important foundation to determine the limit values of water quality standards, which has extreme significance for environmental pollution and control. Based on existing toxicological data as well as numerical calculation and derivation, U.S. Environmental Protection Agency has established water quality criteria aiming at several typical chlorophenol compounds to protect human health and aquatic life (list in *Table 4*). Water quality criteria for human health represents the maximum allowable pollutants concentrations, which will not have deleterious health effects through eating aquatic animals or drinking water. The criteria for protecting aquatic life of specific pollutants represent the minimum concentrations that does not result in a significant risk to most aquatic organisms, including acute and chronic toxicity values.

Depending on the analysis results from the collected literatures, concentrations of several chlorophenol compounds in water environment of many important rivers or lakes such as Haihe River, Yellow River and Dongting Lake apparently exceeded the water quality criteria for human health and aquatic life, which posed potential risks and threats to local human health and ecological environments. However, for those that did not exceed the criteria in most rivers or lakes, suspended particles played an important part in the regulation of chemical toxicity on aquatic organisms as showed in the present analysis, which indicated that potential risk and threat would still exist while suspended particles were present. For a further protection of water quality and aquatic organisms, it is necessary to predict appropriate criteria for watershed with relatively high concentration of suspended particles based on our analysis.

**Table 4.** *Water quality criteria for protecting human health and aquatic life/μg·L$^{-1}$*

| Compounds | Criteria for protecting human health consumption of water and organism | | Criteria for protecting aquatic life (fresh water) | |
|---|---|---|---|---|
| | Water + organism | Organism only | Acute toxicity | Chronic toxicity |
| 2,4-DCP | 10 | 60 | — | — |
| 2,4,5- TCP | 1.5 | 2.8 | — | — |
| 2,4,6-TCP | 300 | 600 | — | — |
| 2-CP | 30 | 800 | — | — |
| PCP | 0.03 | 0.04 | 19 | 15 |

## Conclusions

The occurrence of chlorophenol compounds in aquatic environments including waters, sediments and in organisms were summarized through literature retrieval, classification and analysis. It was shown that various chlorophenol compounds were ubiquitously detected in aquatic environments including waters, sediments and organisms in China, particularly numerous applications of PCP or NaPCP present wide pollution and distributions. PCP was the most ubiquitous chlorophenol with the highest residue appearing especially in the water environment of Dongting lake and Yangtze River, and in the sediment environment and organisms of Dongting lake. Meanwhile, on the other hand, the latest research data also reflect that the pollution levels of PCP, especially in surface waters and organisms in some heavily polluted areas of China, have been greatly reduced compared with the past. Multiple comparison between occurrence, toxicity and water quality criteria of chlorophenol compounds showed more


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appropriate criteria are needed for better protection of human health and aquatic organisms based on the analysis of chemicals toxicity to aquatic organisms in the case of suspended particles. In future studies, we need to focus on the influence of suspended particles in natural water setting on the toxicity of chlorophenol compounds. The joint acute toxicity and accumulation dynamics study of suspended particles and chlorophenol compounds in the future experiments can facilitate to develop an ecotoxicological model for the evaluation of the ecological harm of these chemicals and formulate relevant water quality criteria.

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